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Activity Report 2014

Project-Team I4S

Statistical Inference for Structural Health Monitoring

RESEARCH CENTER
Rennes - Bretagne-Atlantique

THEME
Optimization and control of dynamic systems

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Project-Team I4S

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2. Overall Objectives

2.1. Overall Objectives

monitoring, system identification, change detection, diagnostics, on-line identification and detection algorithms, subspace-based algorithms, statistical hypotheses testing, sensors fusion, optimal sensors placement, vibration-based structural analysis and damage detection and localization, aeronautics, civil engineering

2.1.1. Resume

The objective of this team is the development of Structural Health Monitoring techniques by in particular intrinsic coupling of statistics and thermo-aeroelastic coupling modeling for the development of robust and autonomous structural health monitoring solutions of mechanical structures. The emphasis of the team is the handling of very large systems such as the recent wind energy converters currently being installed in Europe, building on the expertise acquired by the proposed team on bridges as an example of civil engineering structure, and for aircrafts and helicopters in the context of aero elastic instability monitoring. The necessity of system identification and damage detection systems robust to environmental variations and being designed to handle a very large model dimension motivates us. As examples, the explosion in the installed number of sensors and the robustness to temperature variation will be the main focus of the team. This implies new statistical and numerical technologies as well as improvements on the modeling of the underlying physical models. Many techniques and methods originate from the mechanical community and thus exhibit a very deep understanding of the underlying physics and mechanical behavior of the structure. On the other side, system identification techniques developed within the control community are more related to data modeling and take into account the underlying random nature of measurement noise. Bringing these two communities together is the objective of this joint team between Inria and IFSTTAR. It will results hopefully in methods numerically robust, statistically efficient and also mixing modeling of both the uncertainties related to the data and the associated complex physical models related to the laws of physics and finite element models.

Damage detection in civil structures has been a main focus over the last decade. Still, those techniques need to be matured to be operable and installed on structures in operation, and thus be robust to environmental nuisances. Then, damage localization, quantification and prognosis should be in that order addressed by the team. To be precise and efficient, it requires correct mixing between signal processing, statistical analysis, Finite Elements (FEM) Models updating and a yet to be available precise modeling of the environmental effects such as temperature through 3D field reconstruction.

Theoretical and practical questions are more and more complex. For example, in civil engineering, from handling hundreds of sensors automatically during some long period of time to localize and quantify damage with or without numerical models. Very large heavily instrumented structures are yet to come and they will ask for a paradigm in how we treat them from a renewed point of view. As the structures become large and complex, also the thermal and aeroelastic (among other) modeling becomes complex. Bridges and aircraft have been the main focus of our research of the past and still will be our concern. Opening our expertise on new applications topics such as helicopters and wind energy converters is also part of our priorities.

2.1.1.1. Objectives

The main objectives of the team are first to pursue current algorithmic research activities, in order to accommodate still-to-be-developed complex physical models. More precisely, we want successively

- To develop statistical algorithms robust to noise and variation in the environment
- Handle transient and highly varying systems under operational conditions
- To consider the impact of uncertainties on the current available identification algorithms and develop efficient, robust and fast implementation of such quantities
- To consider relevant non trivial thermal models for usage in rejection based structural health monitoring and more generally to mix numerical model, physical modeling and data
- To develop theoretical and software tools for monitoring and localization of damages on civil structures or instability for aircrafts
- To explore new paradigms for handling of very large and complex structures heavily instrumented with new challenges (distributed computing)
- To study the characteristics of the monitored mechanic structures in terms of electromagnetic propagation, in order to develop monitoring methods based on electrical instrumentations.
- To consider society concerns (damage quantification and remaining life prognosis)

2.1.2. Introduction to physics driven dynamical models in the context of civil engineering elastic structures

The design and maintenance of flexible structures subject to noise and vibrations is an important topic in civil and mechanical engineering. It is an important component of comfort (cars and buildings) and contributes significantly to the safety related aspects of design and maintenance (aircrafts, aerospace vehicles and payloads, long-span bridges, high-rise towers...). Requirements from these application areas are numerous and demanding.

Detailed physical models derived from first principles are developed as part of system design These models involve the dynamics of vibrations, sometimes complemented by other physical aspects (fluid-structure interaction, aerodynamics, thermodynamics).

Laboratory and in-operation tests are performed on mock-up or real structures, in order to get so-called modal models, ie to extract the modes and damping factors (these correspond to system poles), the mode shapes (corresponding eigenvectors), and loads. These results are used for updating the design model for a better fit to data, and sometimes for certification purposes (e.g. in flight domain opening for new aircrafts, reception for large bridges).

The monitoring of structures is an important activity for the system maintenance and health assessment. This is particularly important for civil structures. Damaged structures would typically exhibit often very small changes in their stiffness due to the occurrence of cracks, loss of prestressing or post tensioning, chemical reactions, evolution of the bearing behavior and most importantly scour. A key difficulty is that such system characteristics are also sensitive to environmental conditions, such as temperature effects (for civil structures), or external loads (for aircrafts). In fact these environmental effects usually dominate the effect of damage. This is why, for very critical structures such as aircrafts, detailed active inspection of the structures is performed as part of the maintenance. Of course, whenever modal information is used to localize a damage, the localization of a damage should be expressed in terms of the physical model, not in terms of the modal model used in system identification. Consequently, the following elements are encountered and must be jointly dealt with when addressing these applications: design models from the system physics, modal models used in structural identification, and, of course, data from sensors. Corresponding characteristics are given now: Design models are Finite Element models, sometimes with tens or hundreds of thousands elements, depending on professional habits which may vary from one sector to another. These models are linear if only small vibrations are considered; still, these models can be large if medium-frequency spectrum of the load is significant. In addition, nonlinearities enter as soon as large vibrations or other physical effects (aerodynamics, thermodynamics, ..) are considered. Moreover stress-strain paths and therefore the response (and load) history comes into play.

Sensors can range from a handful of accelerometers or strain gauges, to thousands of them, if NEMS (Nano Electro Mechanical Structures), MEMS (Microelectromechanical systems) or optical fiber sensors are used. Moreover, the sensor output can be a two-dimensional matrix if electro magnet (IR (infrared), SAR, shearography ...) or other imaging technologies are used.

2.1.2.1. Multi-fold thermal effects

The temperature constitutes an often dominant load because it can generate a deflection as important as that due to the self-weight of a bridge. In addition, it sometimes provokes abrupt slips of bridge spans on their bearing devices, which can generate significant transient stresses as well as a permanent deformation, thus contributing to fatigue.

But it is also well-known that the dynamic behavior of structures under monitoring can vary under the influence of several factors, including the temperature variations, because they modify the stiffness and thus the modes of vibration. As a matter of fact, depending on the boundary conditions of the structure, possibly uniform thermal variations can cause very important variations of the spectrum of the structure, up to 10%, because in particular of additional prestressing, not forgetting pre strain, but also because of the temperature dependence of the characteristics of materials. As an example, the stiffness of elastomeric bearing devices vary considerably in the range of extreme temperatures of moderate countries. Moreover, eigenfrequencies and modal shapes do not depend monotonically with temperature. Abrupt dynamical behavior may show up due to a change of boundary conditions e.g. due to limited expansion or frost bearing devices. The temperature can actually modify the number of contact points between the piles and the main span of the bridge. Thus the environmental effects can be several orders of magnitude more important than the effect of true structural damages. It will be noted that certain direct methods aiming at detecting local curvature variations stumble on the dominating impact of the thermal gradients. In the same way, the robustness and effectiveness of model-based structural control would suffer from any unidentified modification of the vibratory behavior of the structure of interest. Consequently, it is mandatory to cure dynamic sensor outputs from thermal effects before signal processing can help with a diagnostics on the structure itself, otherwise the possibility of reliable ambient vibration monitoring of civil structures remains questionable. Despite the paramount interest this question deserves, thermal elimination still appears to challenge the SHM community.

2.1.2.2. Toward a multidisciplinary approach

Unlike previously mentioned blind approaches, successful endeavours to eliminate the temperature from subspace-based damage detection algorithms prove the relevance of relying on predictive thermo-mechanical models yielding the prestress state and associated strains due to temperature variations. As part of the CONSTRUCTIF project supported by the Action Concertée Incitative Sécurité Informatique of the French Ministry for Education and Research, very encouraging results in this direction were obtained and published. they were substantiated by laboratory experiments of academic type on a simple beam subjected to a known uniform temperature. Considering the international pressure toward reliable methods for thermal elimination, these preliminary results pave the ground to a new SHM paradigm. Moreover, for one-dimensional problems, it was shown that real time temperature identification based on optimal control theory is possible provided the norm of the reconstructed heat flux is properly chosen. Finally, thermo-mechanical models of vibrating thin structures subject to thermal prestress, prestrain, geometric imperfection and damping have been extensively revisited. This project led by Inria involved IFSTTAR where the experiments were carried out. The project was over in July 2006. Note that thermo-mechanics of bridge piles combined with an *ad hoc* estimation of thermal gradients becomes of interest to practicing engineers. Thus, I4S's approach should suit advanced professional practice. Finite element analysis is also used to predict stresses and displacements of large bridges in Hong-Kong bay .

Temperature rejection is the primary focus and obstacle for SHM projects I4S participates in civil engineering, like SIMS project in Canada, ISMS in Danemark or SIPRIS in France.

A recent collaboration between Inria and IFSTTAR has demonstrated the efficiency of refractometry-based methods for health monitoring of some civil engineering structures, notably external post-tensioned cables. Based on a mathematical model of electromagnetic propagation in mechanical structures, the measurement of reflected and transmitted electromagnetic waves by the monitored structures allows to detect structural failures. The interaction of such methods with those based on mechanical and thermal measurements will reinforce the multidisciplinary approach developed in our team.

2.1.2.3. Models for monitoring under environmental changes - scientific background

We will be interested in studying linear stochastic systems, more precisely, assume at hand a sequence of observations Y_n measured during time,

$$\left\{ \begin{array}{rcl} X_{n+1} & = & AX_n + V_n \\ Y_n & = & HX_n \end{array} \right. \tag{1}$$

where V_n is a zero mean process, A is the transition matrix of the system, H is the observation matrix between state and observation, and X_n the process describing the monitored system. X_n can be related to a physical process (for example, for a mechanical structure, the collection of displacements and velocities at different points). Different problems arise

1/ identify and characterize the structure of interest. It may be possible by matching a parametric model to the observed time series Y_n in order to minimize some given criterion, whose minimum will be the best approximation describing the system,

2/ decide if the measured data describe a system in a so called "reference" state (the term "reference" is used in the context of fault detection, where the reference is considered to be safe) and monitor its deviations with respect of its nominal reference state.

Both problems should be addressed differently if

1/ we consider that the allocated time to measurement is large enough, resulting in a sequence Y_n whose size tends to infinity, a requirement for obtaining statistical convergence results. It corresponds to the identification and monitoring of a dynamical system with slow variations. For example, this description is well suited to the long-term monitoring of civil structures, where records can be measured during relatively (to sampling rate) large periods of time (typically many minutes or hours).

2/ we are interested in systems, whose dynamic is fast with respect to the sampling rate, most often asking for reaction in terms of seconds. It is, for example, the case for mission critical applications such as in-flight control or real-time security and safety assessment. Both aeronautics and transport or utilities infrastructures are concerned. In this case, fast algorithms with sample-by-sample reaction are necessary.

The monitoring of mechanical structures can not be addressed without taking into account the close environment of the considered system and their interactions. Typically, monitored structures of interest do not reside in laboratory but are considered in operational conditions, undergoing temperature, wind and humidity variations, as well as traffic, wind, water flows and other natural or man-made loads. Those variations do imply a variation of the eigenproperties of the monitored structure, variations to be separated from the damage/instability induced variations.

For example, in civil engineering, an essential problem for in operation health monitoring of civil structures is the variation of the environment itself. Unlike laboratory experiments, civil structure modal properties change during time as temperature and humidity vary. Traffic and comparable transient events also influence the structures. Thus, structural modal properties are modified by slow low variations, as well as fast transient non stationarities. From a damage detection point of view, the former has to be detected, whereas the latter has to be neglected and not perturb the detection. Of course, from a structural health monitoring point of view the knowledge of the true load is in itself of paramount importance.

In this context, the considered perturbations will be of two kinds, either

1/ the influence of the temperature on civil structures, such as bridges or wind energy converters : as we will notice, those induced variations can be modeled by a additive component on the system stiffness matrix depending on the current temperature, as

$$K = K_{struct} + K_T \ .$$

We will then have to monitor the variations in K_{struct} independently of the variations in K_T, based on some measurements generated from a system, whose stiffness matrix is K.

2/ the influence of the aeroelastic forces on aeronautical structures such as aircrafts or rockets and on flexible civil structures such as long-span bridges : we will see as well that this influence implies a modification of the usual mechanical equation (2) as

$$M\ddot{Z} + C\dot{Z} + KZ = V \tag{2}$$

where (M, C, K) are the mass, damping and stiffness matrices of the system and Z the associated vector of displacements measured on the monitored structure. In a first approximation, those quantities are related by (2). Assuming U is the velocity of the system, adding U dependent aeroelasticity terms, as in (3), introduces a coupling between U and (M, C, K).

$$M\ddot{Z} + C\dot{Z} + KZ = U^2 DZ + UE\dot{Z} + V \tag{3}$$

Most of the research at Inria since 10 years has been devoted to the study of subspace methods and how they handle the problems described above.

Model (2) is characterized by the following property (we formulate it for the single sensor case, to simplify notations): Let $y_{-N} \cdots y_{+N}$ be the data set, where N is large, and let M, P sufficiently smaller than N for the following objects to make sense: 1/ define the row vectors $Y_k = (y_k \cdots y_{k-M}), |k| \leq P$; 2/ stack the Y_k on top of each other for $k = 0, 1, \cdots, P$ to get the data matrix $\mathcal{Y}_+$ and stack the column vectors Y_k^T for $k = 0, -1, \cdots, -P$ to get the data matrix $\mathcal{Y}_-$; 3/ the product $\mathcal{H} = \mathcal{Y}_+ \mathcal{Y}_-$ is a Hankel matrix. Then, matrix $\mathcal{H}$ on the one hand, and the observability matrix $\mathcal{O}(H, F)$ of system (2) on the other hand, possess almost identical left kernel spaces, asymptotically for M, N large. This property is the basis of subspace identification methods. Extracting $\mathcal{O}(H, F)$ using some Singular Value Decomposition from $\mathcal{H}$ then (H, F) from $\mathcal{O}(H, F)$ using a Least Square approach has been the foundation of the academic work on subspace methods for many years. The team focused on the numerical efficiency and consistency of those methods and their applicability on solving the problems above.

There are numerous ways to implement those methods. This approach has seen a wide acceptance in the industry and benefits from a large background in the automatism literature. Up to now, there was a discrepancy between the a prior efficiency of the method and some not so efficient implementations of this algorithm. In practice, for the last ten years, stabilization diagrams have been used to handle the instability and the weakness with respect to noise, as well as the poor capability of those methods to determine model orders from data. Those methods implied some engineering expertise and heavy post processing to discriminate between model models and noise. This complexity has leads the mechanical community to adopt preferably frequency domain methods such as Polyreference LSCF over the years. Our focus has been on improving the numerical stability of the subspace algorithms by studying how to compute the least square solution step in this algorithm. This yields to a very efficient noise free algorithm, which in the past year has provided a renewed acceptance in the mechanical engineering community for the subspace algorithms. In the past years we focused on improving speed and robustness of those algorithms.

Subspace methods can also be used to test whether a given data set conforms a model: just check whether this property holds, for a given pair {data, model}. Since equality holds only asymptotically, equality must be tested against some threshold ε; tuning ε relies on so-called *asymptotic local* approach for testing between close hypotheses on long data sets — this method was introduced by Le Cam in the 70s. By using the Jacobian between pair (H, F) and the modes and mode shapes, or the Finite Element Model parameters, one can localize and assess the damage.

In oder to discriminate between damage and temperature variations, we need to monitor the variations in K_{struct} while keeping blind to the variations in K_T in statistical terms, we must detect and diagnose changes in K_{struct} while rejecting nuisance parameter K_T. Several techniques were explored in the thesis of Houssein Nasser, from purely empirical approaches to (physical) model based approaches. Empirical approaches do work, but model based approaches are the most promising and a focus of our future researches. This approach requires a physical model of how temperature affects stiffness in various materials. This is why a large part of our future research is devoted to the modeling of such environmental effect.

This approach has been used also for flutter monitoring in the thesis of Rafik Zouari for handling the aeroelastic effect.

2.1.3. PEGASE platform development

We have developed a generic wireless platform that can be considered as the a result of redundant needs in wireless monitoring especially applied to civil engineering monitoring applications. This platform includes software and hardware bricks and aims at being generic by its native implementation of sober components, the worldwide TCP/IP protocol (802.11g), a signal processor, a small GPS receiver, and a micro embedded operating system (μClinux).

Since 2009, this platform -named PEGASE - is subject of an industrial transfer that has generated some tens of individual sales. A set of pluggable boards (that integrate the application specific sensing operation) offers a ready-to-use panel of wireless sensing solutions for developing specific applications as well as they can be seen as prototyping boards for further electronic developments.

As PEGASE platform reached a mature level of dissemination, IFSTTAR recent efforts are now leaded with the goal of improving its wireless capacities. Those works concern energy saving while keeping a high level of embedded processing, of sampling rate or time-synchronization.

As software layers are mainly written in standard C language under Linux OS, those pragmatic solutions could easily be re-used by even radically different systems. The focus will specifically be pointed on: an algorithm that allows PEGASE wireless boards to be synchronized up to some uS using a GPS technique while keeping the GPS receiver OFF most of the time; a description of how the use of an operating system such as μClinux allows a full and remotely update of wireless sensors; the hardware and software strategies that have been developed to make PEGASE fully autonomous using solar cells.

The main characteristics of PEGASE feature are the following:

- Use of TCP/IP/WiFi as the wireless protocol: reliable, low-cost, scalable (IP is the worldwide protocol). Turned OFF when PEGASE doesn't communicate.
- Use of the Analog Device low-power Blackfin BF537 as core processor (Digital Signal Processor): 16 bits processor able of complex operations.
- Implementation of a small and low-power GPS receiver to ensure localization and, first of all, absolute time synchronization up to few μ ms GMT.
- μClinux as the embedded operating system: allows high level of abstraction while PEGASE algorithms are then programmed using standard ANSI C language.

Since its first version on January 2008, PEGASE has been used in various configurations where its properties fitted specific needs. Since a third-party partner (A3IP company) has been licensed by IFSTTAR, PEGASE has been sold in hundreds of specimens and implemented in various configurations. This dissemination proved the capacity of wireless systems to really answer a large spectrum of applications. Developments in progress have the goal to increase this panoply. Even if μClinux and WiFi integration could be considered as *heavy*, the result is a great ability for developers or customers to achieve their own applications. The genericity of C language and the worldwide IP protocol make them ubiquitous. A quite expert job has been leaded to develop specific embedded drivers under μClinux OS in order to get specific behaviors for time synchronization, quartz drift auto-training and correction. This specific and dynamic correction takes temperature effects into account and the result is an absolute time synchronisation better that 4 μS. Even if technologies evolve (components, processor, batteries...), generic principle could be extracted independently from technological choices. Those main principles are: daughter/mother boards, Linux integration, a ready to use c-object library, a boost circuit linked to a MPPT algorithm, GPS synchronization and quartz correction. Most of the improvements can be reused and applied to other wireless platforms even using drastically different electronic implementations.

PEGASE platform has the goal to represent an adapted tool to help companies and laboratories in their instrumentation needs in Civil Engineering applications, Structural Health Monitoring in general and for Non Destructive Techniques tools design. Initial version of PEGASE has been sold in hundreds of samples in France or Europe to small or significant companies such as Vinci, Eurovia, SNCF, Cofiroute...

3. Research Program

3.1. Introduction

In this section, the main features for the key monitoring issues, namely identification, detection, and diagnostics, are provided, and a particular instantiation relevant for vibration monitoring is described.

It should be stressed that the foundations for identification, detection, and diagnostics, are fairly general, if not generic. Handling high order linear dynamical systems, in connection with finite elements models, which call for using subspace-based methods, is specific to vibration-based SHM. Actually, one particular feature of model-based sensor information data processing as exercised in I4S, is the combined use of black-box or semi-physical models together with physical ones. Black-box and semi-physical models are, for example, eigenstructure parameterizations of linear MIMO systems, of interest for modal analysis and vibration-based SHM. Such models are intended to be identifiable. However, due to the large model orders that need to be considered, the issue of model order selection is really a challenge. Traditional advanced techniques from statistics such as the various forms of Akaike criteria (AIC, BIC, MDL, ...) do not work at all. This gives rise to new research activities specific to handling high order models.

Our approach to monitoring assumes that a model of the monitored system is available. This is a reasonable assumption, especially within the SHM areas. The main feature of our monitoring method is its intrinsic ability to the early warning of small deviations of a system with respect to a reference (safe) behavior under usual operating conditions, namely without any artificial excitation or other external action. Such a normal behavior is summarized in a reference parameter vector θ_0, for example a collection of modes and mode-shapes.

3.2. Identification

The behavior of the monitored continuous system is assumed to be described by a parametric model $\{\mathbf{P}_\theta\,,\,\theta\in\Theta\}$, where the distribution of the observations $(Z_0, ..., Z_N)$ is characterized by the parameter vector $\theta\in\Theta$. An *estimating function*, for example of the form :

$$\mathcal{K}_N(\theta) = 1/N\sum_{k=0}^{N} K(\theta, Z_k)$$

is such that $\mathbf{E}_\theta[\mathcal{K}_N(\theta)] = 0$ for all $\theta\in\Theta$. In many situations, $\mathcal{K}$ is the gradient of a function to be minimized : squared prediction error, log-likelihood (up to a sign), ... For performing model identification on the basis of observations $(Z_0, ..., Z_N)$, an estimate of the unknown parameter is then [63] :

$$\widehat{\theta}_N = \arg\{\theta\in\Theta\;:\;\mathcal{K}_N(\theta) = 0\}$$

In many applications, such an approach must be improved in the following directions :

- *Recursive estimation:* the ability to compute $\widehat{\theta}_{N+1}$ simply from $\widehat{\theta}_N$;
- *Adaptive estimation:* the ability to *track* the true parameter θ^* when it is time-varying.

3.3. Detection

Our approach to on-board detection is based on the so-called asymptotic statistical local approach, which we have extended and adapted [5], [4], [2]. It is worth noticing that these investigations of ours have been initially motivated by a vibration monitoring application example. It should also be stressed that, as opposite to many monitoring approaches, our method does not require repeated identification for each newly collected data sample.

For achieving the early detection of small deviations with respect to the normal behavior, our approach generates, on the basis of the reference parameter vector θ_0 and a new data record, indicators which automatically perform :

- The early detection of a slight mismatch between the model and the data;
- A preliminary diagnostics and localization of the deviation(s);
- The tradeoff between the magnitude of the detected changes and the uncertainty resulting from the estimation error in the reference model and the measurement noise level.

These indicators are computationally cheap, and thus can be embedded. This is of particular interest in some applications, such as flutter monitoring.

As in most fault detection approaches, the key issue is to design a *residual*, which is ideally close to zero under normal operation, and has low sensitivity to noises and other nuisance perturbations, but high sensitivity to small deviations, before they develop into events to be avoided (damages, faults, ...). The originality of our approach is to :

- *Design* the residual basically as a *parameter estimating function*,
- *Evaluate* the residual thanks to a kind of central limit theorem, stating that the residual is asymptotically Gaussian and reflects the presence of a deviation in the parameter vector through a change in its own mean vector, which switches from zero in the reference situation to a non-zero value.

This is actually a strong result, which transforms any detection problem concerning a parameterized stochastic *process* into the problem of monitoring the mean of a Gaussian *vector*.

The behavior of the monitored system is again assumed to be described by a parametric model $\{\mathbf{P}_\theta \, , \, \theta \in \Theta\}$, and the safe behavior of the process is assumed to correspond to the parameter value θ_0. This parameter often results from a preliminary identification based on reference data, as in module 3.2.

Given a new N-size sample of sensors data, the following question is addressed : *Does the new sample still correspond to the nominal model* $\mathbf{P}_{\theta_0}$ *?* One manner to address this generally difficult question is the following. The asymptotic local approach consists in deciding between the nominal hypothesis and a *close* alternative hypothesis, namely :

$$\text{(Safe) } \mathbf{H}_0 : \ \theta = \theta_0 \quad \text{and} \quad \text{(Damaged) } \mathbf{H}_1 : \ \theta = \theta_0 + \eta/\sqrt{N} \tag{4}$$

where η is an unknown but fixed change vector. A residual is generated under the form :

$$\zeta_N = 1/\sqrt{N} \sum_{k=0}^{N} K(\theta_0, Z_k) = \sqrt{N} \, \mathcal{K}_N(\theta_0) \ . \tag{5}$$

If the matrix $\mathcal{J}_N = -\,\mathbf{E}_{\theta_0}[\partial \mathcal{K}_N(\theta_0)]$ converges towards a limit $\mathcal{J}$, then, under mild mixing and stationarity assumptions, the central limit theorem shows [62] that the residual is asymptotically Gaussian :

$$\zeta_N \xrightarrow[N \to \infty]{} \begin{cases} \mathcal{N}(0, \Sigma) & \text{under } \mathbf{P}_{\theta_0} \ , \\ \\ \mathcal{N}(\mathcal{J}\,\eta, \Sigma) & \text{under } \mathbf{P}_{\theta_0 + \eta/\sqrt{N}} \ , \end{cases} \tag{6}$$

where the asymptotic covariance matrix Σ can be estimated, and manifests the deviation in the parameter vector by a change in its own mean value. Then, deciding between $\eta = 0$ and $\eta \neq 0$ amounts to compute the following χ^2-test, provided that $\mathcal{J}$ is full rank and Σ is invertible :

$$\chi^2 = \bar{\zeta}^T \, \mathbf{F}^{-1} \, \bar{\zeta} \gtrless \lambda \ . \tag{7}$$

where

$$\overline{\zeta} \triangleq \mathcal{J}^T \Sigma^{-1} \zeta_N \quad \text{and} \quad \mathbf{F} \triangleq \mathcal{J}^T \Sigma^{-1} \mathcal{J} \tag{8}$$

With this approach, it is possible to decide, with a quantifiable error level, if a residual value is significantly different from zero, for assessing whether a fault/damage has occurred. It should be stressed that the residual and the sensitivity and covariance matrices $\mathcal{J}$ and Σ can be evaluated (or estimated) for the nominal model. In particular, it is *not* necessary to re-identify the model, and the sensitivity and covariance matrices can be pre-computed off-line.

3.4. Diagnostics

A further monitoring step, often called *fault isolation*, consists in determining which (subsets of) components of the parameter vector θ have been affected by the change. Solutions for that are now described. How this relates to diagnostics is addressed afterwards.

The question: *which (subsets of) components of θ have changed ?*, can be addressed using either nuisance parameters elimination methods or a multiple hypotheses testing approach [61].

In most SHM applications, a complex physical system, characterized by a generally non identifiable parameter vector Φ has to be monitored using a simple (black-box) model characterized by an identifiable parameter vector θ. A typical example is the vibration monitoring problem for which complex finite elements models are often available but not identifiable, whereas the small number of existing sensors calls for identifying only simplified input-output (black-box) representations. In such a situation, two different diagnosis problems may arise, namely diagnosis in terms of the black-box parameter θ and diagnosis in terms of the parameter vector Φ of the underlying physical model.

The isolation methods sketched above are possible solutions to the former. Our approach to the latter diagnosis problem is basically a detection approach again, and not a (generally ill-posed) inverse problem estimation approach [3]. The basic idea is to note that the physical sensitivity matrix writes $\mathcal{J}\,\mathcal{J}_{\Phi\theta}$, where $\mathcal{J}_{\Phi\theta}$ is the Jacobian matrix at Φ_0 of the application $\Phi \mapsto \theta(\Phi)$, and to use the sensitivity test for the components of the parameter vector Φ. Typically this results in the following type of directional test :

$$\chi^2_\Phi = \zeta^T \Sigma^{-1} \mathcal{J}\,\mathcal{J}_{\Phi\theta}\,(\mathcal{J}^T_{\Phi\theta}\,\mathcal{J}^T\,\Sigma^{-1}\,\mathcal{J}\,\mathcal{J}_{\Phi\theta})^{-1}\,\mathcal{J}^T_{\Phi\theta}\,\mathcal{J}^T\,\Sigma^{-1}\,\zeta \gtrless \lambda \; . \tag{9}$$

It should be clear that the selection of a particular parameterization Φ for the physical model may have a non negligible influence on such type of tests, according to the numerical conditioning of the Jacobian matrices $\mathcal{J}_{\Phi\theta}$.

As a summary, the machinery in modules 3.2, 3.3 and 3.4 provides us with a generic framework for designing monitoring algorithms for continuous structures, machines and processes. This approach assumes that a model of the monitored system is available. This is a reasonable assumption within the field of applications since most mechanical processes rely on physical principles which write in terms of equations, providing us with models. These important *modeling* and *parameterization* issues are among the questions we intend to investigate within our research program.

The key issue to be addressed within each parametric model class is the residual generation, or equivalently the choice of the *parameter estimating function*.

3.5. Subspace-based identification and detection

For reasons closely related to the vibrations monitoring applications, we have been investigating subspace-based methods, for both the identification and the monitoring of the eigenstructure (λ, ϕ_λ) of the state transition matrix F of a linear dynamical state-space system :

$$\left\{ \begin{array}{rcl} X_{k+1} & = & F\ X_k + V_{k+1} \\ Y_k & = & H\ X_k \end{array} \right. , \tag{10}$$

namely the $(\lambda, \varphi_\lambda)$ defined by :

$$\det\ (F - \lambda\ I) = 0, \quad (F - \lambda\ I)\ \phi_\lambda = 0, \quad \varphi_\lambda \triangleq H\ \phi_\lambda \tag{11}$$

The (canonical) parameter vector in that case is :

$$\theta \triangleq \begin{pmatrix} \Lambda \\ \text{vec}\Phi \end{pmatrix} \tag{12}$$

where Λ is the vector whose elements are the eigenvalues λ, Φ is the matrix whose columns are the φ_λ's, and vec is the column stacking operator.

Subspace-based methods is the generic name for linear systems identification algorithms based on either time domain measurements or output covariance matrices, in which different subspaces of Gaussian random vectors play a key role [64]. A contribution of ours, minor but extremely fruitful, has been to write the output-only covariance-driven subspace identification method under a form that involves a parameter estimating function, from which we define a *residual adapted to vibration monitoring* [1]. This is explained next.

3.5.1. Covariance-driven subspace identification.

Let $R_i \triangleq \mathbf{E}\left(Y_k\ Y_{k-i}^T\right)$ and:

$$\mathcal{H}_{p+1,q} \triangleq \begin{pmatrix} R_0 & R_1 & \vdots & R_{q-1} \\ R_1 & R_2 & \vdots & R_q \\ \vdots & \vdots & \vdots & \vdots \\ R_p & R_{p+1} & \vdots & R_{p+q-1} \end{pmatrix} \triangleq \text{Hank}\left(R_i\right) \tag{13}$$

be the output covariance and Hankel matrices, respectively; and: $G \triangleq \mathbf{E}\left(X_k Y_k^T\right)$. Direct computations of the R_i's from the equations (10) lead to the well known key factorizations :

$$\begin{array}{rcl} R_i & = & HF^iG \\ \mathcal{H}_{p+1,q} & = & \mathcal{O}_{p+1}(H,F)\ \mathcal{C}_q(F,G) \end{array} \tag{14}$$

where:

$$\mathcal{O}_{p+1}(H,F) \triangleq \begin{pmatrix} H \\ HF \\ \vdots \\ HF^p \end{pmatrix} \quad \text{and} \quad \mathcal{C}_q(F,G) \triangleq (G\ FG\ \cdots\ F^{q-1}G) \tag{15}$$

are the observability and controllability matrices, respectively. The observation matrix H is then found in the first block-row of the observability matrix $\mathcal{O}$. The state-transition matrix F is obtained from the shift invariance property of $\mathcal{O}$. The eigenstructure (λ, ϕ_λ) then results from (11).

Since the actual model order is generally not known, this procedure is run with increasing model orders.

3.5.2. Model parameter characterization.

Choosing the eigenvectors of matrix F as a basis for the state space of model (10) yields the following representation of the observability matrix:

$$\mathcal{O}_{p+1}(\theta) = \begin{pmatrix} \Phi \\ \Phi\Delta \\ \vdots \\ \Phi\Delta^p \end{pmatrix} \tag{16}$$

where $\Delta \stackrel{\Delta}{=} \text{diag}(\Lambda)$, and Λ and Φ are as in (12). Whether a nominal parameter θ_0 fits a given output covariance sequence $(R_j)_j$ is characterized by [1]:

$$\mathcal{O}_{p+1}(\theta_0) \text{ and } \mathcal{H}_{p+1,q} \text{ have the same left kernel space.} \tag{17}$$

This property can be checked as follows. From the nominal θ_0, compute $\mathcal{O}_{p+1}(\theta_0)$ using (16), and perform e.g. a singular value decomposition (SVD) of $\mathcal{O}_{p+1}(\theta_0)$ for extracting a matrix U such that:

$$U^T\, U = I_s \text{ and } U^T\, \mathcal{O}_{p+1}(\theta_0) = 0 \tag{18}$$

Matrix U is not unique (two such matrices relate through a post-multiplication with an orthonormal matrix), but can be regarded as a function of θ_0. Then the characterization writes:

$$U(\theta_0)^T\, \mathcal{H}_{p+1,q} = 0 \tag{19}$$

3.5.3. Residual associated with subspace identification.

Assume now that *a reference* θ_0 *and a new sample* $Y_1, \cdots, Y_N$ *are available.* For checking whether the data agree with θ_0, the idea is to compute the empirical Hankel matrix $\widehat{\mathcal{H}}_{p+1,q}$:

$$\widehat{\mathcal{H}}_{p+1,q} \stackrel{\Delta}{=} \text{Hank}\left(\widehat{R}_i\right), \quad \widehat{R}_i \stackrel{\Delta}{=} 1/(N-i) \sum_{k=i+1}^{N} Y_k\, Y_{k-i}^T \tag{20}$$

and to define the residual vector:

$$\zeta_N(\theta_0) \stackrel{\Delta}{=} \sqrt{N} \text{ vec}\left(U(\theta_0)^T\, \widehat{\mathcal{H}}_{p+1,q}\right) \tag{21}$$

Let θ be the actual parameter value for the system which generated the new data sample, and $\mathbf{E}_\theta$ be the expectation when the actual system parameter is θ. From (19), we know that $\zeta_N(\theta_0)$ has zero mean when no change occurs in θ, and nonzero mean if a change occurs. Thus $\zeta_N(\theta_0)$ plays the role of a residual.

It is our experience that this residual has highly interesting properties, both for damage detection [1] and localization [3], and for flutter monitoring [8].

3.5.4. Other uses of the key factorizations.

Factorization (3.5.1) is the key for a characterization of the canonical parameter vector θ in (12), and for deriving the residual. Factorization (14) is also the key for :

- Proving consistency and robustness results [6];
- Designing an extension of covariance-driven subspace identification algorithm adapted to the presence and fusion of non-simultaneously recorded multiple sensors setups [7];
- Proving the consistency and robustness of this extension [9];
- Designing various forms of *input-output* covariance-driven subspace identification algorithms adapted to the presence of both known inputs and unknown excitations [10].

3.5.5. Research program

The research will first focus on the extension and implementation of current techniques as developed in I4S and IFSTTAR. Before doing any temperature rejection on large scale structures as planned, we need to develop good and accurate models of thermal fields. We also need to develop robust and efficient versions of our algorithms, mainly the subspace algorithms before envisioning linking them with physical models. Briefly, we need to mature our statistical toolset as well as our physical modeling before mixing them together later on.

3.5.5.1. Direct vibration modeling under temperature changes

This task builds upon what has been achieved in the CONSTRUCTIF project, where a simple formulation of the temperature effect has been exhibited, based on relatively simple assumptions. The next step is to generalize this modeling to a realistic large structure under complex thermal changes. Practically, temperature and resulting structural prestress and pre strains of thermal origin are not uniform and civil structures are complex. This leads to a fully 3D temperature field, not just a single value. Inertia effects also forbid a trivial prediction of the temperature based on current sensor outputs while ignoring past data. On the other side, the temperature is seen as a nuisance. That implies that any damage detection procedure has first to correct the temperature effect prior to any detection.

Modeling vibrations of structures under thermal prestress does and will play an important role in the static correction of kinematic measurements, in health monitoring methods based on vibration analysis as well as in durability and in the active or semi-active control of civil structures that by nature are operated under changing environmental conditions. As a matter of fact, using temperature and dynamic models the project aims at correcting the current vibration state from induced temperature effects, such that damage detection algorithms rely on a comparison of this thermally corrected current vibration state with a reference state computed or measured at a reference temperature. This approach is expected to cure damage detection algorithms from the environmental variations.

I4S will explore various ways of implementing this concept, notably within the FUI SIPRIS project.

3.5.5.2. Damage localization algorithms (in the case of localized damages such as cracks)

During the CONSTRUCTIF project, both feasibility and efficiency of some damage detection and localization algorithms were proved. Those methods are based on the tight coupling of statistical algorithms with finite element models. It has been shown that effective localization of some damaged elements was possible, and this was validated on a numerical simulated bridge deck model. Still, this approach has to be validated on real structures.

On the other side, new localization algorithms are currently investigated such as the one developed conjointly with University of Boston and tested within the framework of FP7 ISMS project. These algorithms will be implemented and tested on the PEGASE platform as well as all our toolset.

When possible, link with temperature rejection will be done along the lines of what has been achieved in the CONSTRUCTIF project.

3.5.5.3. Uncertainty quantification for system identification algorithms

Some emphasis will be put on expressing confidence intervals for system identification. It is a primary goal to take into account the uncertainty within the identification procedure, using either identification algorithms derivations or damage detection principles. Such algorithms are critical for both civil and aeronautical structures monitoring. It has been shown that confidence intervals for estimation parameters can theoretically be related to the damage detection techniques and should be computed as a function of the Fisher information matrix associated to the damage detection test. Based on those assumptions, it should be possible to obtain confidence intervals for a large class of estimates, from damping to finite elements models. Uncertainty considerations are also deeply investigated in collaboration with Dassault Aviation in Mellinger PhD thesis or with Northeastern University, Boston, within Gallegos PhD thesis.

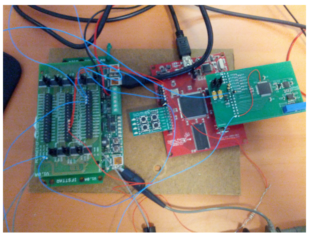
3.5.5.4. Reflectometry-based methods for civil engineering structure health monitoring

For mechanical structures with a dominating geometrical axis so that they can be approximately considered one dimensional structures, some reflectometry-based methods initially developed for electrical cable monitoring have proved efficient for their health monitoring. Typical applications of such methods have been validated for the monitoring of external post-tensioned cables built with concrete bridges. Further studies are necessary to generalize this technology to other mechanical structures.

3.5.5.5. PEGASE platform

A new iteration called PEGASE 2 of our wireless platform has to be finalized (see Software section), in particular:

- Validation of PEGASE 2 mother board for its ability to recover energy from solar cells. Writing resulting abacus and user-guides...
- Discover and manage the DSP Library of PEGASE 2 (TI 5330 processor)
- Finalizing its main daughter boards:
  - 8 synchronous analog channel daughter board (finalized at 90
  - validation of the POE (Power Over Ethernet) daughter board
  - validation of the 3G daughter board (for GSM links)
  - Finalizing the supervisor (Matlab plugin...)



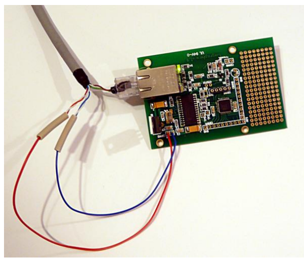


Figure 1. PEGASE board

4. Application Domains

4.1. Civil Engineering

For at least three decades, monitoring the integrity of the civil infrastructure has been an active research topic because of major economical and societal issues, such as durability and safety of infrastructures, buildings and networks. Control of civil structures began a century ago. At stake is the mastering either the aging of the bridges, as in America (US, Canada) and Great Britain, or the resistance to seismic events and the protection of the cultural heritage, as in Italy and Greece. The research effort in France is very ancient since for example early developments of optical methods to monitor civil structures began in the 70s and SHM practice can be traced back to the 50s with the vibrating wire sensors as strain gauges for dams. Stille the number of sensors actually placed on civil structures is kept to a minimum, mainly for cost reasons, but also because the return on investment sensing and data processing technologies is not properly established for civil structures. One of the current thematic priorities of the C2D2 governmental initiative is devoted to construction monitoring and diagnostics. The picture in Asia (Japan, and also China) is somewhat different, in that recent or currently built bridges are equipped with hundreds if not thousands of sensors, in particular the Hong Kong-Shenzen Western Corridor and Stonecutter Bridge projects. However, the actual use of available data for operational purpose remains unclear.

Among the challenges for vibration-based bridges health monitoring, two major issues are the different kinds of (non measured) excitation sources and the environmental effects. Typically the traffic on *and* under the bridge, the wind and also the rain, contribute to excite the structure, and influence the measured dynamics. Moreover, the temperature is also known to affect the eigenfrequencies and mode-shapes, to an extent which can be significant w.r.t. the deviations to be monitored.

Thermomechanical prestress states affect the dynamic and the static behavior of most bridges, not only of very long and flexible ones. So, the reliable and fast determination of the state of prestress and prestrain associated with a temperature field becomes a crucial step in several engineering processes such as the health monitoring of civil structures. The best possible reconstruction of the temperature field could then become part of a complete process including massively distributed sensing of thermomechanical information on the structure, modeling and algorithms for the on-line detection of damages in the sense of abnormalities with regard to a nominal state, the whole chain being encapsulated in professional tools used by engineers in charge of real-life structural monitoring. For lack of an adequate mobilization of the useful multidisciplinary skills, this way remains about unexplored today.

4.2. Electrical cable and network monitoring

The fast development of electronic devices in modern engineering systems comes with more and more connections through cables, and consequently, the reliability of electric connections becomes a crucial issue. For example, in a modern automotive vehicle, the total length of onboard cables has tremendously increased during the last decades and is now up to 4km. These wires and connectors are subject to aging or degradation because of severe environmental conditions. In this area, reliability becomes a safety issue. In some other domains, cable defects may have catastrophic consequences. It is thus a crucial challenge to design smart embedded diagnosis systems able to detect wired connection defects in real time. This fact has motivated research projects on methods for fault diagnosis in electric transmission lines and wired networks. Original methods have been recently developed by Inria, notably based on the inverse scattering theory, for cable and network monitoring. Further developments concern both theoretic study and industrial applications.

4.3. Aeronautics

Improved safety and performance and reduced aircraft development and operating costs are major concerns in aeronautics industry. One critical design objective is to clear the aircraft from unstable aero-elastic vibrations (flutter) in all flight conditions. Opening of flight domain requires a careful exploration of the dynamical behavior of the structure subject to vibration and aero-servo-elastic forces. This is achieved via a combination of ground vibration tests and in flight tests. For both types of tests, various sensors data are recorded, and modal analyses are performed. Important challenges of the in-flight modal analyses are the limited choices for measured excitation inputs, and the presence of unmeasured natural excitation inputs (turbulence). Today, structural flight tests require controlled excitation by ailerons or other devices, stationary flight conditions (constant elevation and speed), and no turbulence. As a consequence, flight domain opening requires a lot of test flights and its costly. This is even worse for aircrafts having a large number of variants (business jets, military aircrafts). A key challenge is therefore to allow for exploiting more data under more conditions during flight tests: uncontrolled excitation, nonstationary conditions.

5. New Software and Platforms

5.1. ISTL

Participant: Qinghua Zhang.

ISTL is a software realizing numerical computations of the inverse scattering transform for electrical transmission lines. It provides an efficient solution to experimentally determining the distributed characteristic impedance of an electrical transmission line from the reflection coefficient measured at one end of the line. Its current applications are in the fields of electrical cable fault diagnosis and of civil engineering structure monitoring. In addition to inverse scattering transform algorithms, ISTL includes a numerical simulator generating reflection coefficients of user-specified transmission lines and a graphical user interface. It is registered at Agence pour la Protection des Programmes (APP) under the number IDDN.FR.001.120003.000.S.P.2010.000.30705. See http://people.rennes.inria.fr/Qinghua.Zhang/istl.html.

5.2. PEGASE

Participants: Vincent Le Cam, Mathieu Le Pen, Laurent Mevel, Michael Doehler.

I4S is actually finalizing the setup of a new platform named PEGASE 2.0 as the technological successor of the previous PEGASE platform developed by IFSTTAR.

The new version of PEGASE keeps the best of its previous version in its main vocation, to be a generic high level Wireless Sensor Platofrm.

- What does not change between PEGASE 1 and 2.0: Based on various feedback from application fields, results from real structures monitored by PEGASE, and due to the rapid obsolescence of electronic devices, the design of the new PEGASE platform has been launched in 2013. Some of the main functions of PEGASE does not change but are reinforced.
  - Software genericity: use of a Linux embedded OS to make any application developed independently from the hardware, to make the user able to manage the system without ant physical and heavy operations.
  - Hardware genericity: with a principle of daughter and mother boards, each redundant need is embedded (processing, memory, timing, GPS, energy, etc) which each pluggable daughter board implements a specific function (sensing, 3G, Ethernet, communication, signal processing and relay control).
  - Accurate time synchronization: based on an original GPS and PPS algorithm, PEGASE platform is one of the only board able to time-stamp data from sensors or any event with an accuracy of some micro-seconds Universal Time.
- What's new on PEGASE 2 platform ?

  Previous principles are maintained or extended. Full electronic design from scratch occurred in 2014 to maximise its capacities in terms efficiency, cost, energy consumption, etc. Its main characteristics are
  - Important software evolutions: the platform embedded a real Linux kernel (not μClinux as previously done for memory size questions). This new kernel allows the perception of PEGASE 2 as real PC (without screen and mouse) providing important functions as MMU, software upgrade.
  - Important hardware evolutions and integration

    * A very advanced GPS module (Ublox Neo 6T) to allow more accurate time synchronization (up to 100 nanoseconds)
    * An embedded energy harvesting module (and not from a daughter board as previously done) to recover energy from DC sources if available or a solar cell, while managing the low of dis/charging Lithium-Ion battery and the MMPT algorithms
  – A Single Development Kit (SDK) fully (re) coded in C++ (and not C-object as proposed before) that permit a real capitalization of software developments and knowledges implemented (such as algorithms for SHM). Based on an UML model
- A major evolution in PEGASE concept consists in providing a generic web-tool to monitor PEGASE platform (whatever is the version) and many others wireless and commercial devices. A reproach addressed to previous concept resides in the fact that PEGASE was too focused on providing a generic wireless platform. But a quite big work was still necessary to monitor the devices. This new concept has been already sold to companies (such as SNCF or Cofiroute) and allows:
  – To create one independent instance of the Supervisor by client
  – Each instance of the Supervisor works 100% in the cloud with a secured access (https + login/password). Thus final users can operate it from anywhere in the world : at instrumented site level as at desk or during travel, etc.
  – For each client, the possibility to create an infinity of instrumentation projects
  – For each instrumentation project, to associate as many sensors as required by the application. Sensors can be PEGASE 1 or PEGASE 2 boards as many others : Labjack devices, some National Instruments acquisition boards, Meteo-France sources...

  The list of the devices known by the Supervisor is open and is supposed, year after year, to be completed. Thus, next PEGASE projects aims at providing not only some wireless sensors platform but also a modern, full-clouded, monitoring application. Moreover the 2015 $R\&D$ program plans to add a very interesting function from the scientific point of view: a Matlab plug-in. The idea consists in linking the data flow managed by supervisor directly and automatically to some Matlab sources codes uploaded on the web platform. The Supervisor will compile the original Matlab files. They are dynamically compiled on an embedded Matlab runtime library on the cloud server. Thus, once the the specifications about data format are written and took into account by developers, scientist can dynamically test and operate its Matlab models uploaded on the Supervisor.

6. New Results

6.1. Highlights of the Year

The team organized the 7th European Workshop on SHM in Nantes in July 2014 (http://ewshm2014.com) .

6.2. Analysis and control of systems

6.2.1. Optimal vibration damping of large structures

Participant: Dominique Siegert.

This paper deals with the theoretical and experimental analysis of magnetically tuned mass dampers, applied to the vibration damping of large structures of civil engineering interest. Two devices are analysed, for which both the frequency tuning ratio and the damping coefficient can be easily and finely calibrated. They are applied for the damping of the vibrations along two natural modes of a mock-up of a bridge under construction. An original analysis, based on the Maxwell receding image method, is developed for estimating the drag force arising inside the damping devices. It also takes into account self inductance effects, yielding a complex nonlinear dependence of the drag force on the velocity. The analysis highlights the range of velocities for which the drag force can be assumed of viscous type, and shows its dependence on the involved geometrical parameters of the dampers. The model outcomes are then compared to the corresponding experimental calibration curves. A dynamic model of the controlled structure equiped with the two damping devices is presented, and used for the development of original optimization expressions and for determining the corresponding maximum achievable damping. Finally, several experimental results are presented, concerning both the free and harmonically forced vibration damping of the bridge mock-up, and compared to the corresponding theoretical predictions. The experimental results reveal that the maximum theoretical damping performance can be achieved, when both the tuning frequencies and damping coefficients of each device are finely calibrated according to the optimization expressions [15], [46].

6.2.2. Particle filtering techniques for monitoring of structures

Participant: Laurent Mevel.

The focus of this paper is Bayesian modal parameter recursive estimation based on an interacting Kalman filter algorithm with decoupled distributions for frequency and damping. Interacting Kalman filter is a combination of two widely used Bayesian estimation methods: the particle filter and the Kalman filter. Some sensitivity analysis techniques are also proposed in order to deduce a recursive estimate of modal parameters from the estimates of the damping/stiffness coefficients [30].

6.2.3. Uncertainty quantification

Participants: Michael Doehler, Laurent Mevel.

For applications as Operational Modal Analysis (OMA) of vibrating structures, an output-only LTI system with state and measurement noise can be identified using subspace methods. While these identification techniques have been very suitable for the identification of such mechanical, aeronautical or civil structures, covariance expressions of the estimates of the system matrices are difficult to obtain and theoretical results from literature are hard to implement for output-only systems with unknown noise properties in practice. Moreover, the model order of the underlying system is generally unknown and due to noise and model errors, usual statistical criteria cannot be used. Instead, the system is estimated at multiple model orders and some GUI driven stabilization diagram containing the resulting modal parameters is used by the structural engineer. Then, the covariance of the estimates at these different model orders is an important information for the engineer, which, however, would be computationally expensive to obtain with the existing tools. Recently a fast multi-order version of the stochastic subspace identification approach has been proposed, which is based on the use of the QR decomposition of the observability matrix at the largest model order. In this paper, the corresponding covariance expressions for the system matrix estimates at multiple model orders are derived and successfully applied on real vibration data [38], [40].

6.2.4. Periodic systems

Participants: Ivan Guéguen, Laurent Mevel.

The modal analysis of a wind turbine has been generally handled with the assumption that this structure can be accurately modeled as linear time-invariant. Such assumption may be misleading for stability analysis, especially, with the current development of very large wind turbines with complex dynamic behavior (nonlinearity, aeroelastic coupling). Therefore in this paper, the inherent periodically time-varying dynamics of wind turbines (and for rotating systems, in general) is taken into account. Recently a subspace algorithm for modal analysis of rotating systems has been proposed. It is tested on a simulated and real data from a wind turbine [22], [43].

6.2.5. Identification of finite impulse response systems based on quantized output measurements – a quadratic programming-based method

Participant: Qinghua Zhang.

This work has been carried out in collaboration with Jiandong Wang (Peking University, China).

Quantized data are typically produced by the process of analog-to-digital conversion and have been widely studied in signal encoding and digital representation. In system identification, the processed data are usually collected after a quantization procedure, but the effect of quantization is often ignored. The study on system identification based on quantized data makes sense when the data are coded with few quantization levels, to the point that the effect of quantization becomes important. In this work we propose a quadratic programming (QP)-based method for identification of finite impulse response (FIR) dynamic systems from quantized or binary data. The main idea of the proposed method is to reformulate this identification problem, usually viewed as a nonlinear estimation problem with discontinuous nonlinearities, in the form of a standard QP problem, which is a convex optimization problem and can be solved efficiently. The complete input conditions ensuring the strict convexity of the QP problem are developed, and the consistency of the estimated parameters is established under the complete input conditions. The results of this study have been published in [29].

6.2.6. Wiener System Identification by Weighted Principal Component Analysis

Participant: Qinghua Zhang.

This work has been carried out in collaboration with Vincent Laurain (CRAN/CNRS/Université de Lorraine).

A Wiener system consists of two subsystems connected in series, with a linear dynamic subsystem preceding a static nonlinearity. In the field of control systems, the dynamics of a nonlinear system can often be linearized around its working point. Nevertheless, if its output sensor is affected by strongly nonlinear distortions, the linearization of the sensor characteristics may induce large modeling errors. In such situations, Wiener system model is more appropriate than fully linearized models. Wiener system identification is investigated in this work with a finite impulse response (FIR) model of the linear subsystem. Under the assumption of Gaussian input distribution, this work mainly aims at addressing a deficiency of the well-known correlation-based method for Wiener system identification: it fails when the nonlinearity of the Wiener system is an even function. This method is, in the considered Gaussian input case, equivalent to the best linear approximation (BLA) method, which exhibits the same deficiency. Our new method is based on a weighted principal component analysis (wPCA). Its consistency is proved for Wiener systems with either even or non even nonlinearities. Its computational cost is almost the same as that of a standard PCA.The results of this study have been presented at [53].

6.2.7. Industrial process for road buildings

Participant: Jean Dumoulin.

The increasing use of the baffled-rotary kiln equipment in many innovative materials processing industrial applications suggests examining the heat transfer phenomena in order to improve the multi-phase flow modeling tools. Their development and use will be relevant for tackling the current energy issues. The heat transfer models available for the rotary kiln in the literature are, for now, not enough efficient for the baffled-rotary kiln case. The present paper is aimed at suggesting a wall heat transfer correlation for the rotary kilns with the secondary inlet. The experimental thermal data acquired within large-scale rotary drum applied to the asphalt concrete materials production, are remained in order to give rise the new issues. These latter results are connected to a visualization campaign performed at the pilot-scale in order to assess the transversal distribution of the granular phase materials. Their analysis suggests a more appropriate physical modelling of the wall heat transfer path. It leads to transform the classical correlation of type $Nu = f(Re, Pr)$ in a new expression of type $Nu = f(Re, St)$ based on a new physical modeling inventory corresponding to the hot and cold fluxes flowing within the baffled-rotary kiln. Thus, the major modification is based on the introduction of the Stanton (St) number in the wall heat transfer correlation. This expression is found more convenient for the baffled-rotary kiln application. This new expression is validated by the comparison with the experimental Nusselt numbers calculated from the inner heat transfer measurements coefficient measured in the baffled-rotary kiln performed at large scale [23].

6.2.8. Industrial process for concrete structure reparation

Participant: Jean Dumoulin.

In civil engineering, reinforced concrete repair by CFRP is a strengthening technique that has proven successfully in the past. The present study is aimed at using thermoplastic CFRP sheets applied and glued under heat. In this research framework, active thermography is used to accomplish two roles: control of the operating temperature of the thermoplastic CFRP sheets during the installation process and evaluation of the bonding quality after welding. The pap er presents results obtained in laboratory with a dedicated test bench coupled with numerical simulations of the process [51].

6.2.9. Building energy management

Participants: Alexandre Nassiopoulos, Jordan Brouns.

Problems such as parameter identification for model calibration, optimal design or optimal energy management can all be formulated in a similar framework as problems consisting in finding the minimum of a cost function. The paper presents the software ReTrofiT that specifically treats this kind of problems applied to building energy performance models. ReTrofiT is first of all a simulation tool for evaluating building thermal behavior and computing energy consumptions. The novelty compared to state-of-the-art energy simulation software is that it also integrates a generic set of tools and algorithms to set up and solve optimization problems related to the building thermal model. The use of the adjoint model, that is intrinsically implemented in the code, constructs fast and efficient algorithms to solve linear, non linear, constrained or unconstrained problems addressing a wide range of applications [45].

6.3. damage detection for mechanical structures

6.3.1. Damage detection and localisation

Participants: Michael Doehler, Luciano Gallegos, Laurent Mevel.

The Stochastic Dynamic Damage Locating Vector approach is a vibration-based damage localization method based on a finite element model of a structure and output-only measurements in both reference and damaged states. A stress field is computed for loads in the null space of a surrogate of the change in the transfer matrix at the sensor positions for some values in the Laplace domain. Then, the damage location is related to positions where the stress is close to zero. Robustness of the localization information can be achieved by aggregating results at different values in the Laplace domain. So far, this approach and in particular the aggregation is deterministic and does not take the uncertainty in the stress estimates into account. In this paper, the damage localization method is extended with a statistical framework. The uncertainty in the output-only measurements is propagated to the stress estimates at different values of the Laplace variable and these estimates are aggregated based on statistical principles. The performance of the new statistical approach is demonstrated both in a numerical application and a lab experiment, showing a significant improvement of the robustness of the method due to the statistical evaluation of the localization information [24], [39].

6.3.2. An Innovations Approach to Fault Diagnosis in Linear Time-Varying Descriptor Systems

Participant: Qinghua Zhang.

This work has been carried out in collaboration with Abdouramane Moussa-Ali (LSIS/CNRS/Université de Toulon).

Many modern engineering systems can be modeled by explicit ordinary differential equations (ODE) in state-space form. Such state-space equations have a long-term mathematical history, and a large number of analytical and numerical tools have been developed for their study. Nevertheless, some systems cannot be described by such explicit state-space models, but described by *implicit* differential equations, known as differential-algebraic equations (DAE). After linearization along a trajectory and discretization in time, a nonlinear DAE system is approximately described by *implicit* discrete time state-space equations, known as *descriptor system equations*. In this work, fault diagnosis is studied for time varying descriptor systems. The Kalman filter for descriptor systems is first revisited by completing existing results about its properties that are essential for the purpose of fault diagnosis. Based on the analysis of the effects of the considered actuator and sensor faults on the innovation of the descriptor system Kalman filter, it is shown that the considered fault diagnosis problem in time varying descriptor systems is equivalent to a classical linear regression problem formulated by appropriately filtering the input-output data. Following this result, algorithms for fault diagnosis through maximum likelihood estimation are then developed. The results of this study have been presented at [44].

6.3.3. Statistical detection and isolation of additive faults in linear time-varying systems

Participant: Qinghua Zhang.

This work has been carried out in collaboration with Michèle Basseville (IRISA/CNRS).

Model-based approaches to fault detection and isolation (FDI) have been mostly studied in the literature for linear time invariant (LTI) systems. In practice, quite often time-varying and/or nonlinear properties of the monitored system cannot be neglected. One of the possible approachs to dealing with nonlinear systems is based on the linearization along the actual or nominal trajectory of the monitored system. Such a linearization generally leads to linear time-varying (LTV) systems, whereas the more basic LTI approximation is usually related to the linearization around a single working point. It is thus clear that methods for FDI in LTV systems are much more powerful than their LTI counterparts. In the present work, we address the FDI problem for LTV systems subject to parametric additive faults. The proposed approach is statistical, by combining a generalized likelihood ratio (GLR) test with the Kalman filter that cancels out the dynamics of the faults effects in the considered LTV systems. With this approach, it is possible to perform fault isolation when the number of sensors is smaller than the number of assumed faults, under an appropriate assumption about the excitation of the system. The results of this study have been published in [31].

6.3.4. Robust subspace damage detection

Participants: Michael Doehler, Laurent Mevel.

In the last ten years, monitoring the integrity of the civil infrastructure has been an active research topic, including in connected areas as automatic control. It is common practice to perform damage detection by detecting changes in the modal parameters between a reference state and the current (possibly damaged) state from measured vibration data. Subspace methods enjoy some popularity in structural engineering, where large model orders have to be considered. In the context of detecting changes in the structural properties and the modal parameters linked to them, a subspace-based fault detection residual has been recently proposed and applied successfully, where the estimation of the modal parameters in the possibly damaged state is avoided. However, most works assume that the unmeasured ambient excitation properties during measurements of the structure in the reference and possibly damaged condition stay constant, which is hardly satisfied by any application. This paper addresses the problem of robustness of such fault detection methods. It is explained why current algorithms from literature fail when the excitation covariance changes and how they can be modified. Then, an efficient and fast subspace-based damage detection test is derived that is robust to changes in the excitation covariance but also to numerical instabilities that can arise easily in the computations. Three numerical applications show the efficiency of the new approach to better detect and separate different levels of damage even using a relatively low sample length [20], [37], [19].

6.3.5. Sensor placement

Participant: Michael Doehler.

Deciding on the position of sensors by optimizing the utility of the monitoring system over a structure lifetime is typically forbidden by computational cost. Sensor placement strategies are, instead, usually formulated for a pre-selected number of sensors and are based on cost functions that can be evaluated for any arrangement without the need for simulations. This paper examines the performance of two such schemes, the first one is derived directly from a technique that detects damage from the shift of a chi-square distribution from central to non-central and takes the optimal arrangement as the one that maximizes the sensitivity of the non-centrality to all parameter changes of equal norm. The second scheme selects the sensor arrangement as that which maximizes a weighted version of the norm of the sensitivity of the covariance of the output to all feasible changes in system parameters. The performance of the two schemes is tested in simulations [34].

6.3.6. Reflectometry for external post-tensioned cable monitoring

Participant: Qinghua Zhang.

This work has been carried out in collaboration with IFSTTAR, EDF, ENS Cachan and Andra.

Nowadays a considerable number of bridges is reaching an age when repairs become necessary. In some bridges, external post-tension cables are placed in ducts within which the residual internal space is imperfectly filled with a fluid cement grout. Detecting the defaults of filling is visually impossible from the outside. Among non-destructive detection techniques proposed for cable health monitoring, reflectometry techniques offer remarkable advantages in that they can monitor cables in concrete deviator (embedded in concrete) and they do not require human intervention inside the bridge. In this work, the application of reflectometry techniques to cable health monitoring has been investigated via numerical simulations and laboratory experiments. The results of this study have been presented at [55].

6.3.7. Efficient Computation of Minmax Tests for Fault Isolation and Their Application to Structural Damage Localization

Participants: Michael Doehler, Laurent Mevel.

Fault detection and isolation can be handled by many different approaches. This paper builds upon a hypothesis test that checks whether the mean of a Gaussian random vector has become non-zero in the faulty state, based on a chi2 test. For fault isolation, it has to be decided which components in the parameter set of the Gaussian vector have changed, which is done by variants of the chi2 hypothesis test using the so-called sensitivity and minmax approaches. While only the sensitivity of the tested parameter component is taken into account in the sensitivity approach, the sensitivities of all parameters are used in the minmax approach, leading to better statistical properties at the expense of an increased computational burden. The computation of the respective test variable in the minmax test is cumbersome and may be ill-conditioned especially for large parameter sets, asking hence for a careful numerical evaluation. Furthermore, the fault isolation procedure requires the repetitive calculation of the test variable for each of the parameter components that are tested for a change, which may be a significant computational burden. In this paper, dealing with the minmax problem, we propose a new efficient computation for the test variables, which is based on a simultaneous QR decomposition for all parameters. Based on this scheme, we propose an efficient test computation for a large parameter set, leading to a decrease in the numerical complexity by one order of magnitude in the total number of parameters. Finally, we show how the minmax test is useful for structural damage localization, where an asymptotically Gaussian residual vector is computed from output-only vibration data of a mechanical or a civil structure [41].

6.3.8. Inverse problems in damage detection

Participant: Dominique Siegert.

Reinforced concrete beams are widely employed in civil engineering structures. To reduce the maintenance financial cost, structure damages have to be detected early. To this end, one needs robust monitoring techniques. The paper deals with the identification of mechanical parameters, useful for Structural Health Monitoring, in a 2D beam using inverse modeling technique. The optimal control theory is employed. As an example, we aim to identify a reduction of the steel bar cross-section and a decrease of the concrete Young modulus in damaged areas. In our strategy, the beam is instrumented with strain sensors, and a known dynamic load is applied. In the inverse technique, two space discretizations are considered: a fine dicretization to solve the structural dynamic problem and a coarse discretization for the beam parameter identification. To get the beam parameters, we minimize a classical data misfit functional using a gradient-like algorithm. A low-cost computation of the functional gradient is performed using the adjoint equation. The inverse problem is solved in a general way using engineer numerical tools: Python scripts and the free finite element software Code Aster. First results show that a local reduction of the steel bar cross-section and a local decrease of concrete Young modulus can be detected using this inverse technique [27].

6.3.9. NDT by active thermography coupled with infrared shearography

Participant: Jean Dumoulin.

As infrastructures are aging, the evaluation of their health is becoming crucial. To do so, numerous Non Destructive Testing (NDT) methods are available. Among them, thermal shearography and active infrared thermography represent two full field and contactless methods for surface inspection. The synchronized use of both methods presents multiples advantages. Most importantly, both NDT are based on different material properties. Thermography depend on the thermal properties and shearography on the mechanical properties. The cross-correlation of both methods result in a more accurate and exact detection of the defects. For real site application, the simultaneous use of both methods is simplified due to the fact that the excitation method (thermal) is the same. Active infrared thermography is the measure of the temperature by an infrared camera of a surface subjected to heat flux. Observation of the variation of temperature in function of time reveal the presence of defects. On the other hand, shearography is a measure of out-of-plane surface displacement. This displacement is caused by the application of a strain on the surface which (in our case) take the form of a temperature gradient inducing a thermal stress [58], [49], [50].

6.4. Long term monitoring of civil engineering structure

6.4.1. ICT based software for thermal field long term monitoring of civil engineering structures

Participants: Antoine Crinière, Jean Dumoulin.

Aging of transport infrastructures combined with traffic and climatic solicitations contribute to the reduction of their performances. To address and quantify the resilience of civil engineering structure, investigations on robust, fast and efficient methods are required. Among research works carried out at IFSTTAR, methods for long term monitoring face an increasing demand. Such works take benefits of this last decade technological progresses in ICT domain. A multi-sensing techniques system, able to date and synchronize measurements carried out by infrared thermography coupled with various measurements data (i.e. weather parameters), have been designed, developed and implemented on real site. This smart sensor called IrLaw/SENSORBOX has been upgraded in order to reach full autonomy and its able to monitor over years civil engineering structures [57], [17], [36].

6.4.2. Long term structural health monitoring architecture

Participant: Jean Dumoulin.

This work gives a brief description of the main activities and outcomes of the Integrated System for Transport Infrastructures surveillance and Monitoring by Electromagnetic Sensing (ISTIMES – www.istimes.eu) project, which was concerned with the development and implementation of a system able to couple the capabilities of long-term monitoring and quick damage assessment of the critical transport infrastructures. This was performed thanks to the integrated use of the novel and state of art concepts of Earth observation, ground-based sensing techniques and ICT architecture [47], [48].

6.5. Material characterization

6.5.1. Quantitative non destructive testing in civil engineering

Participants: Jordan Brouns, Antoine Crinière, Jean Dumoulin, Alexandre Nassiopoulos.

By the aging of civil engineering structures a crucial need of reparation or reinforcement appeared through years. This can be done using bonded CFRP plate to assure the mechanical behavior of the structure. This type of reparation need diagnosis to insure the reliability of the reparation procedure. This part focus on the development of 1D to 3D method to asses the quantitative non destructive testing of a repaired structure thanks to active thermography (see [16] and [54]).

6.5.2. Thermo-physical characterization for civil engineering application

Participant: Jean Dumoulin.

This papers presents the development of a new device for the determination of thermal conductivity and diffusivity of anisotropic composite plates. The excitation signal is provided through a thermoelectric cooler and does not require any optical source like a laser source for instance. Infrared thermography is used to follow apparent surface temperature evolution with time. Experiments were carried out two composite sample systems (with two different fiber orientations). Result analysis is presented and discussed [42].

6.5.3. Emissivity characterization for civil engineering applications

Participant: Jean Dumoulin.

The knowledge of the infrared emissivity of materials used in buildings and civil engineering structures is useful for two specific approaches. First, quantitative diagnosis of buildings or civil engineering infrastructures by infrared thermography requires emissivity values in the spectral bandwidth of the camera used for measurements, in order to obtain accurate surface temperatures; for instance, emissivity in the band III domain is required when using cameras with uncooled detectors (such as micro-bolometer arrays). Second, setting up accurate thermal balances by numerical modeling requires the total emissivity value for a large wavelength domain; this is, for instance, the case for computing the road surface temperature to predict ice occurrence. Furthermore, periodical surveys of emissivity variations due to aging or soiling of surfaces could be useful in many situations such as thermal mapping of roads or building insulation diagnosis. The use of portable emissivity measurement devices is required for that purpose. A device using an indirect measurement method was previously developed in our lab; the method uses measurement of the reflectivity from a modulated IR source and requires calibration with a highly reflective surface. However, that device uses a low-frequency, thermal modulation well adapted to laboratory measurements but unfit for fast and in situ measurements. Therefore, a new, portable system which retains the principle of an indirect measurement but uses a faster-frequency, mechanical modulation more appropriate to outdoor measurements was developed. Both devices allow measurements in the broad (1μm to 40μm) and narrow (8μm to 40μm) bands. Experiments were performed on a large number of materials commonly used in buildings and civil engineering structures.The final objective of this work is to build a database of emissivity of these materials. A comparison of laboratory and on-site measurements of emissivity values obtained in both spectral bands will be presented along with an estimation and an analysis of measurement uncertainties [25].

6.6. Vision under environmental conditions

6.6.1. Infrared Imaging under environmental conditions

Participant: Jean Dumoulin.

An infrared system has been developed to monitor transport infrastructures in a standalone configuration. It is based on low cost infrared thermal cameras linked with a calculation unit in order to produce a corrected thermal map of the surveyed structure at a selected time step. With the inline version, the data collected feed simplified radiative models running a GPU. With the offline version, the thermal map can be corrected when data are collected under different atmospheric conditions up to foggy night conditions. A model for radiative transmission prediction is proposed and limitations are addressed. Furthermore, the results obtained by image and signal processing methods with data acquired on the transport infrastructure opened to traffic are presented. Finally, conclusions and perspectives for new implementation and new functionalities are presented and discussed [18].

6.6.2. Long term thermal monitoring by uncooled infrared camera

Participant: Jean Dumoulin.

Being able to perform easily non-invasive diagnostics for surveillance and monitoring of critical transport infrastructures is a major preoccupation of many technical offices. Among all the existing electromagnet-icmethods, long term thermal monitoring by uncooled infrared camera is a promising technique due to its dissemination potential according to its low cost on the market. Nevertheless, Knowledge of environmental parameters during measurement in outdoor applications is required to carry out accurate measurement corrections induced by atmospheric effects at ground level. Particularly considering atmospheric effects and measurements in foggy conditions close as possible to those that can be encountered around transport infrastructures, both in visible and infrared spectra. In the present study, atmospheric effects are first addressed by using data base available in literature and modelling. Atmospheric attenuation by particles depends greatly of aerosols density, but when relative humidity increases, water vapor condenses onto the particulates suspended in the atmosphere. This condensed water increases the size of the aerosols and changes their composition and their effective refractive index. The resulting effect of the aerosols on the absorption and scattering of radiation will correspondingly be modified [56].

6.6.3. Handling of fog conditions by infrared cameras

Participant: Jean Dumoulin.

Fog conditions are the cause of severe car accidents in western countries because of the poor induced visibility. Its forecast and intensity are still very difficult to predict by weather services. Infrared cameras allow to detect and to identify objects in fog while visibility is too low for eye detection. Over the past years, the implementation of cost effective infrared cameras on some vehicles has enabled such detection. On the other hand pattern recognition algorithms based on Canny filters and Hough transformation are a common tool applied to images. Based on these facts, a joint research program between IFSTTAR and Cerema has been developed to study the benefit of infrared images obtained in a fog tunnel during its natural dissipation. Pattern recognition algorithms have been applied, specifically on road signs which shape is usually associated to a specific meaning (circular for a speed limit, triangle for an alert, ...). It has been shown that road signs were detected early enough in images, with respect to images in the visible spectrum, to trigger useful alerts for Advanced Driver Assistance Systems [35].

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. PhD CIFRE with EDF

Participants: Nassif Berrabah, Qinghua Zhang.

A joint PhD project between Inria and EDF (Electricité de France) has been started since December 2014. The purpose of this study is to develop methods for the monitoring of electrical cables in power stations, in order to prevent failures caused by aging or accidental events. This project is funded by EDF and by the ANRT agency for three years.

7.1.2. Contracts with SVS

Participants: Laurent Mevel, Michael Doehler.

Annual agreement Inria-SVS 2381 + contract 4329

I4S is doing technology transfer towards SVS to implement I4S technologies into ARTEMIS Extractor Pro. This is done under a royalty agreement between Inria and SVS .

In 2014, the damage detection toolbox has been launched http://www.svibs.com/products/ARTeMIS_Modal_Features/Damage_Detection.aspx.

7.1.3. Contracts with A3IP

Participant: Vincent Le Cam.

A licensing work has been initialized at IFSTTAR in order to sold some licenses of PEGASE 2 to companies who would like to use, modify, extend and sell the functions in the Structural Health Monitoring world. Separate and non-exclusive licenses will be regarded to:

- a) sell the PEGASE 2 devices : mother and daughter boards
- b) sell the PEGASE 2 Supervisor

7.1.4. *PhD CIFRE with Dassault Aviation*

Participants: Laurent Mevel, Philippe Mellinger.

contract 7843.

Following the FliTE2 project, a joint PhD thesis between Inria and Dassault Aviation has been initiated. The thesis pursue the work achieved in FliTE2 and started in June 2011 funded by Dassault Aviation and the ANRT agency. PhD of P. Mellinger has been defended in December 2014.

7.1.5. *Collaboration with Bruel and Kjaer*

Participants: Laurent Mevel, Ivan Guéguen.

Collaboration has started on analysis on wind turbines data. A paper has been presented at EWSHM 2014.

7.1.6. *Contract with SNCF*

Participants: Vincent Le Cam, Mathieu Le Pen.

Deployment of a set of PEGASE platform for SNCF: SNCF has just signed a contract in view of instrumenting 2 railways sites where the needs of wireless and smart sensors has been expressed. I4S contribution will mainly focus on data processing and algorithms implementation.

7.1.7. *Contract with GDF*

Participants: Vincent Le Cam, Mathieu Le Pen.

GDF (national french Gaz company) has signed a wide contract with IFSTTAR relative to many items in Wireless Sensors Networks. One of the items will be prototyped on PEGASE 2 platform and consists in finding an accurate solution for WSN synchronization without GPS source and for an autonomy of 10 years. One of the identified solution will be prototyped on PEGASE 2 as wireless and generic development platform and as it offers an accurate 100 nanoseconds absolute time reference.

7.1.8. *Collaboration with SIEMENS*

Participant: Jean Dumoulin.

Since 2012, a work has been initiated for thermal studies for SIEMENS about subway infrastructures. 2013 was dedicated to the study of thermal instrumentation of subway. 2014 was focused on the instrumentation of a rail mockup in Nantes.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. *FONDEOL2*

Participants: Dominique Siegert, Ivan Guéguen.

Type: Region

Objectif: wind turbines SHM

Duration: June 2011 to June 2014

Coordinator: STX France

Partners: IFSTTAR, Central School of Nantes and EGIS

Inria contact: Ivan Guéguen

Abstract: The project involves innovation supports and foundations for offshore wind around 5 lots representing the issues of the project:

- Lot 1: The design methodology
- Lot 2: Design, calculation, execution and control of offshore foundations
- Lot 3: Structural supports remote monitoring of wind
- Lot 4: Eco-design of supports and foundations for wind jacket and gravity
- Lot 5: Integration of noise reduction during pile installation in foundation design jacket

We are interested in the problem of Lot 3, structural monitoring of wind turbine supports. This lot covers an area of research in full expansion, commonly known as Structural Health Monitoring (SHM).

8.1.2. MAG2C-Pont Tabarly

Participant: Ivan Guéguen.

Type: GIS

Objectif: bridge instrumentation

Duration: Since 2014

Coordinator : LIRGEC

Partners: IFSTTAR, CSTB, Nantes Métropole, Université de Nantes

Inria contact: Ivan Guéguen

Abstract: The project deals with the instrumentation of the Tabarly Bridge.

The instrumentation auscultates globally the structure, a structural defect in a given location changes its modal parameters and thus the vibration behavior. Then it can be detected on any part of the structure with an accelerometer. These measures coupled with a wireless data transmission system type or wifi 3g will allow remote monitoring of the evolution of the structure. And where appropriate, to deploy when necessary, for maintenance. The different objectives are

- Experimentation on a bridge
- Equipment qualification in real conditions over the long term
- Apply different vibration processing algorithms
- Surveillance and Detection
- Measurement database

The instrument proposed is based on an accelerometer-based distributed network on the structure. This assembly is connected to a data acquisition system and a modem 3g for continuous measurements and remotely. The vibration will be collectable on the internet.

8.2. National Initiatives

8.2.1. High speed rail track Instrumentation

Participant: Ivan Guéguen.

Type: IRT

Objectif: bridge SHM

Duration: 11/2014 to 11/2018

Coordinator: RAILENIUM

Partners : IFSTTAR, EIFFAGE, RFF, LGCgE

Inria contact: Ivan Guéguen

Abstract: This project aims to orchestrate multiple sections of a high-speed route (classical section with granular layer, transition zone). The proposed instrumentation concerns all the different layers of the structure, and is designed to allow monitoring of the overall track behavior

The instrumentation will include: A Weather station measures environmental conditions (temperature, precipitation on the site). Accelerometers, to monitor the dynamic behavior of the track, with measures at several levels: the hammer beams on top of the grave-bitumen layer, on top of the soil. These measures will include acceleration compare the dynamic response of a section with and without GB. Instrumentation of severe bitumen strain gauges for measuring the longitudinal and transverse tensile strains at the base of the UK, and temperature probes (top and bottom layer). This instrumentation will estimate the fatigue life of the GB, temperature changes in this layer, and will calculate a temperature equivalent to the layer of GB. Instrumentation subgrade by means of measurement gauges at the top of the vertical deformation of the soil, and TDR probes to measure changes in water content. Its objective is to measure the levels of distortion in the upper part of the soil, and their variations, in conjunction with the seasonal variations in water content. An anchored sensor, measuring the total deflection between the top of the GB and a reference point that is 4 m deep. This sensor will measure the total displacement of the structure beneath the ballast (GB + layer of granular soil leveling + support). These will also serve as a reference for comparison with the movements deducted from accelerometer measurements. Continuous optical fiber, to measure static permanent deformation in the transverse direction over the entire width of the structure at the base of the sub-layer. These optical fibers used to monitor deformation obtained following the transverse profile in the game with underlay in the UK (in ballast) and the part with underlay GNT (Differential settlement, appearance of a crack ...).

8.2.2. REPTILES

Participant: Jean Dumoulin.

Type: FUI

Objectif: Innovation for rehabilitation of potable water tubes

Duration: Since 11/2012

Coordinator: FREYSSINET

Inria contact: J. Dumoulin

Since 2012, within FUI Reptiles, J. Dumoulin was coordinator of the conception, study and development of a thermoplastic composite assembly system for water tubes reenforcement. Moreover, infrared thermography was used for active control.

8.2.3. SIPRIS

Participants: Laurent Mevel, Dominique Siegert, Ivan Guéguen, Vincent Le Cam, Mathieu Le Pen, Michael Doehler.

contract 6841.

Type: FUI

Objectif: Systèmes d'Instrumentation pour la prévention des risques

Duration: June 2013 to June 2014

Coordinator: ADVITAM

Inria contact: L. Mevel

Abstract: The project concerns the behavior of a prestressed concrete beam, a series of vibration and displacement measurement was carried out in line with internal stresses due to the cables. This followed an experimental modal analysis and study of the variations of modal parameters on the beam. As part of the project, the laboratory signaling gantry of IFSTTAR Nantes was instrumented to perform an experimental system for automatic damage detection based on monitoring the natural modes of vibration. The gantry was also modeled by the finite element method to predict the variations of the first natural frequencies of vibration for a damage event catalog. The gantry is a metallic structure of 8x12 m, formed by the assembly of profiled aluminum alloy welded. This portico was installed there thirty years on the site. Each pillar is fixed in a massive concrete anchor with threaded rods 10, which are critical for the stability of the gantry. CAD geometric model made with Solidworks that was used for the mesh structure with shell elements. The FE mesh consists of 59231 triangular elements at 6 knots, the model has a total of 143,831 nodes. The thicknesses of the shells of the parts constituting the structure are between 3 and 25 mm. The mechanical properties of the aluminum alloy are reported in the table below. The boundary conditions applied to the model consisted of blocking the degrees of freedom of movement and rotation on the edges of holes arranged to pass the threaded rods. The mesh is refined in the vicinity of the holes. The results give an excellent correlation between simulation and experiment on the relative value for the third mode. The correlation is smaller for the first and the second mode. An update of the numerical model can refine the correlation between simulation and experiment, especially the absolute value of frequencies. As shown in the simulation and experimentation, modes with greater frequency of changes generally important in their relative value.

Tests were performed on laboratory test slabs SII Nantes

Very good progresses has also been validated compared to the problems encountered on PEGASE 1 due to memory limitations (few memory, no MMU, reduced Linux...). A global method is currently tested: transcoding SSI algorithms from Matlab sources to C codes using the Matlab-coder toolbox. Thus code execution is compared to the results got from Matlab from a common benchmark of data files

8.2.4. Collaboration with ISAE

Participants: Laurent Mevel, Ahmed Jhinaoui.

Ahmed Jhinaoui has finished his thesis on helicopter instability. This thesis was co-directed by professor Morlier from ISAE, France. This thesis is funded by FP7-NMP Large Scale Integrated Project IRIS.

8.2.5. Collaboration with GEM

Participants: Laurent Mevel, Michael Doehler, Md Delwar Hossain Bhuyan.

Md Delwar Hossain Bhuyan has started a PhD on Damage localisation on offshore platforms, The thesis is co-directed by L. Mevel and F. Schoefs from GEM, Nantes, with supervision shared with M. Doehler and Y. Lecieux from GEM. It is funded by the Brittany region for 3 years.

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

8.3.1.1. ISMS

Participants: Michael Doehler, Laurent Mevel.

Type: FP7

Defi: Internet-Based Structural Monitoring System

Instrument: Industry-Academia Partnerships and Pathway

Objectif: Develop damage detection framework for SHM

Duration: September 2010 - August 2014

Coordinator: Palle Andersen

Partner: Structural Vibration Solutions (Denmark), University of British Columbia (Canada)

Inria contact: Laurent Mevel

Abstract:

ISMS aimed to address the significant commercial opportunity and rapidly emerging technological potential of improved Damage Detection or Structural Health Monitoring (SHM) technologies for large-scale civil infrastructure by challenging significant and non-trivial, inter-disciplinary and intersectoral barriers currently preventing industrial application and take-up of these technologies. The principal strategic objective of ISMS was joint design and development of a fully automated internet-based damage detection procedure robust to environmental changes with application to fully instrumented large-scale civil infrastructures, primarily bridges [52].

8.3.2. Collaborations in European Programs, except FP7 & H2020

8.3.2.1. European Research Network on System Identification (ERNSI)

Participants: Qinghua Zhang, Michael Doehler, Laurent Mevel.

The I4S project-team is involved in the activities of the European Research Network on System Identification (ERNSI) federating major European research teams on system identification, currently teams from 8 countries. Modeling of dynamical systems is fundamental in almost all disciplines of science and engineering, ranging from life science to process control. System identification concerns the construction, estimation and validation of mathematical models of dynamical physical or engineering phenomena from experimental data.

8.3.2.2. MODRIO

Participants: Qinghua Zhang, Liangquan Zhang.

Type: ITEA2

Defi: Model Driven Physical Systems Operation

Objectif: To meet the evermore stringent safety and environmental regulations for power plants and transportation vehicles, system operators need new techniques to improve system diagnosis and operation.

Duration: June 2012 to November 2015

Coordinator: Daniel Bouskela (EDF)

Inria teams PARKAS, HYCOMS, I4S

Inria contact: B. Caillaud

Abstract: Open standards are necessary for different teams to cooperate by sharing compatible information and data. The objective of the MODRIO project is to extend modeling and simulation tools based on open standards from system design to system diagnosis and operation. This project joined by partners from Austria, Belgium, Finland, France, Germany, Italy and Sweden has been selected by the board of Information Technology for European Advancement (ITEA 2).

8.3.2.3. COST Action TU 1402

Participants: Michael Doehler, Laurent Mevel.

L. Mevel is member of the management committee of the COST Action.

M. Doehler is co-leader of working group 2 "SHM technologies and structural performance".

Type: COST

Objectif: Quantifying the value of structural health monitoring

Duration: 11/2014 - 11/2018

Coordinator: S. Thoens (DTU Denmark)

Partner: 23 countries, see http://www.cost.eu/COST_Actions/tud/Actions/TU1402

Inria contact: Laurent Mevel

Abstract: This COST Action enhances the benefit of Structural Health Monitoring (SHM) by novel utilization of applied decision analysis on how to assess the value of SHM - even before it is implemented. This improves decision basis for design, operation and life-cycle integrity management of structures and facilitates more cost efficient, reliable and safe strategies for maintaining and developing the built environment to the benefit of society. SHM is increasingly applied for collecting information on loads and aggressive environments acting on structures, structural performances, deterioration processes and changes in the use of structures. However, there is an urgent need to establish a better understanding of the value of SHM before its implementation, together with practically applicable methods and tools for its quantification. This Action thus aims to develop and describe a theoretical framework, together with methods, tools, guidelines, examples and educational activities, for the quantification of the value of SHM. The COST Action will be conducted with the support of the Joint Committee on Structural Safety (JCSS). The networks of researchers and industries established during COST Actions TU0601, C26, E55 and E24, the EU FP7 project IRIS, the Marie Curie Network SmartEn and the JCSS will ensure visibility, impact and dissemination.

8.3.2.4. EBONSI

Participant: Qinghua Zhang.

Type: ANR-NSFC

Objectif: Extended Block-Oriented Nonlinear System Identification

Duration: from April 2011 to March 2014.

Coordinator: Qinghua Zhang

Partner: CRAN, Laboratory of Industrial Process Monitoring and Optimization of Peking University.

Inria contact: Qinghua Zhang

Abstract: The main idea of block-oriented nonlinear system identification is to model a complex system with interconnected simple blocks. Such models can cover a large number of industrial applications, and are yet simple enough for theoretic studies. The objectives of the EBONSI project are to extend classical block-oriented nonlinear models to new model structures motivated by industrial applications, and to relax some traditional restrictions on experimental conditions. This is an international project jointly funded by the French Agence Nationale de la Recherche (ANR) and the Chinese National Natural Science Foundation (NSFC) .

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events organisation

9.1.1.1. general chair, scientific chair

V. Le Cam was general chair of the 7th European Workshop on Structural Health Monitoring in Nantes, from 8 to 11, July 2014.

L. Mevel was scientific chair of the 7th European Workshop on Structural Health Monitoring in Nantes, from 8 to 11, July 2014.

9.1.1.2. member of the organizing committee

M. Doehler was member of the organizing committee of 7th European Workshop on Structural Health Monitoring in Nantes, from 8 to 11, July 2014.

M. Le Pen was member of the organizing committee of 7th European Workshop on Structural Health Monitoring in Nantes, from 8 to 11, July 2014.

Q. Zhang is member of the national organization committee of the IFAC Symposium SAFEPROCESS 2015 (http://safeprocess15.sciencesconf.org/).

9.1.2. Scientific events selection

9.1.2.1. responsable of the conference program committee

V. Le Cam has been nominated head of the EWSHM scientific committee in 2014 (http://ewshm2014.com).

9.1.2.2. member of the conference program committee

L. Mevel

- has been nominated as member of the EWSHM scientific committee in 2014 (http://ewshm2014.com).
- has organized with M. Doehler one invited session at EWSHM 2014 (http://ewshm2014.com)
- is member of the IOMAC scientific committee (http://www.iomac.dk)

J.Dumoulin is

- member of the scientific committee of the GI Division (Geosciences Instrumentation and Data Systems) of EGU for infrastructure instrumentation and monitoring since April 2013.
- member of the committee of QIRT (quantitative Infrared Thermography) since February 2014 (http://qirt2014.scientific-event.com)
- organizer of invited sessions at EWSHM 2014 (http://ewshm2014.com) and TRA 2014 (http://www.traconference.eu).
- organizer of some invited sessions at EGU 2014 (http://www.egu2014.eu).

Q. Zhang is

- member of IFAC Technical Committee on Modelling, Identification and Signal Processing (TC 1.1, http://tc.ifac-control.org/6/4/).
- Member of IFAC Technical Committee on Fault Detection, Supervision and Safety of Technical Processes (TC 6.4, http://tc.ifac-control.org/6/4/).
- Member of the international program committee of the IFAC Symposium SYSID 2015 (http://sysid2015.info/).
- Member of the international program committee of the IFAC Symposium SAFEPROCESS 2015 (http://safeprocess15.sciencesconf.org/).

9.1.2.3. reviewer

L. Mevel, M. Doehler were reviewers for many conferences in 2014 (IFAC WC, CDC, EWSHM, ...).

J. Dumoulin was reviewer for EWSHM 2014 (http://ewshm2014.com) and for the European Signal Processing Conference (EUSIPCO - http://www.eusipco2014.org/).

9.1.3. Journal

9.1.3.1. member of the editorial board

L. Mevel is member of the editorial board of journal of Simulation in Engineering.

L. Mevel is member of the editorial board of journal of Shock and Vibration.

Q. Zhang is member of the editorial board of the journal of Intelligent Industrial Systems.

9.1.3.2. reviewer

L. Mevel was reviewer for Mechanical Systems and Signal Processing, journal of Sound And Vibration, Applied Maths and Computation, Operational Research, journal of CSNDT.

M. Doehler was reviewer for Journal of Electrical Power and Energy Systems and Mechanical Systems and Signal Processing.

L. Mevel and M. Doehler were reviewers for the journal of Smart Materials and Structures.

J. Dumoulin was reviewer for IEEE Transactions on Instrumentation and Measurement, Quantitative Infrared Thermography Journal, Optics and Lasers in Engineering journal , Journal Cultural Heritage, International Journal of Architectural Heritage, Journal of Geophysics and Engineering, Research in Nondestructive Evaluation

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

Licence Professionnelle TAM : J. Dumoulin, thermographie infrarouge active, 8h, Université Paris-Est, France

Master 2 MMMRI, (Maintenance et Maîtrise des Risques Industriels) , J. Dumoulin, contrôle non destructif par thermographie infrarouge active, 12h, Université Paris-Est, France

Master Système Communicant Mobile, V. Le Cam, embedded systems under Linux Operating System, 12h, Polytech Nantes, France

Master Civil engineering, V. Le Cam, Structural Monitoring, 4h, Université de Nantes, France

Licence 3 SEICOM, V. Le Cam, 3h, SHM and smart grids, Université de Nantes, France

Licence 3 SEICOM, V. Le Cam, 8h, TP, SHM and smart grids, Université de Nantes, France

ESEO, V. Le Cam, 8h, TP, embedded systems under Linux Operating System, France

9.2.2. Supervision

PhD : Jordans, Broons, *Développement d'outils numériques pour l'audit énergétique des bâtiments*, Université Paris-Est, A. Nassiopoulos, Frédéric Bourquin (IFSTTAR) and Karim Limam (Université de La Rochelle), Ecole doctorale Science Ingénierie et Environnement (SIE), 01/12/14.

PhD : Ahmed Jhinaoui, *Subspace-based identification and vibration monitoring algorithms for rotating systems*, Université de Rennes 1, L.Mevel and J. Morlier (ISAE), Ecole doctorale MATISSE, defended on May 28th, 2014

PhD : Philippe Mellinger, *Estimation des incertitudes en identification modale avec et sans entrées connues : Théorie, validation et application*, Université de Rennes 1, L. Mevel and C. Meyer (Dassault Aviation), Ecole doctorale MATISSE, defended on December 16th, 2014

PhD : Nassif Berrabah, *Electrical cable aging monitoring*, Q. Zhang, Ecole doctorale MATISSE, Université de Rennes 1, since November 2014

PhD : Delwar Hossain Bhuyan, *Damage localisation on offshore platforms*, L. Mevel and M. Doehler, Ecole doctorale MATISSE, Université de Rennes 1, since November 2014

PhD : Mohamed Oumri, *Diagnostic of defaults in electric networks*, Q. Zhang, Université de PARIS-SUD, 2014. Thesis happened jointly with SISYPHE project at Inria Rocquencourt

Liangquan Zhang's post-doctoral project on hybrid system monitoring, Q. Zhang, 2014-2015.

9.2.3. Juries

J. Dumoulin was part of the jury of A. Crinière at Ecole Centrale de Nantes.

L. Mevel was member of Julie Bessac's PhD defense committee at IRMAR, University of Rennes 1, October 20th, 2014.

L. Mevel was member of Fabien Menant's PhD defense committee at IFSTTAR, Nantes, Ecole Centrale de Nantes, November 4th, 2014.

Q. Zhang was member of Mariem Sahnoun's PhD defense committee at Université de Lyon 1, December 4th, 2014

9.3. Popularization

Qinghua Zhang has published the following work:

Q. Zhang: Encyclopedia article *'Nonlinear system identification – an overview'*, in Encyclopedia of Systems and Control, Springer, 2014, (http://www.springerreference.com/docs/html/chapterdbid/364854.html) [59].

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Major publications by the team in recent years

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[2] M. BASSEVILLE. *On–board component fault detection and isolation using the statistical local approach*, in "Automatica", November 1998, vol. 34, n^o 11, pp. 1391–1416, http://dx.doi.org/10.1016/S0005-1098(98)00086-7

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Doctoral Dissertations and Habilitation Theses

[11] J. BROUNS. *Development of numerical tools for building energy audit*, Université Paris-Est, December 2014, https://tel.archives-ouvertes.fr/tel-01135056

[12] A. CRINIÈRE. *Contribution au développement d'outils d'analyse de séquences d'images infrarouges : Application au contrôle non destructif de structures de Génie Civil*, Centrale nantes, October 2014, https://hal.archives-ouvertes.fr/tel-01111166

[13] P. MELLINGER. *Uncertainty estimation of Input / Output and Output-Only modal identification : theory, validation and application*, Université Rennes 1, December 2014, https://tel.archives-ouvertes.fr/tel-01135711

[14] M. OUMRI. *Fault diagnosis of wired electric networks by reflectometry*, Université Paris-Sud, May 2014, https://hal.inria.fr/tel-01097198

Articles in International Peer-Reviewed Journals

[15] F. BOURQUIN, G. CARUSO, M. PEIGNEY, D. SIEGERT. *Magnetically tuned mass dampers for optimal vibration damping of large structures*, in "Smart Materials and Structures", June 2014, vol. 23, n^{o} 8, 085009 [*DOI :* 10.1088/0964-1726/23/8/085009], https://hal-enpc.archives-ouvertes.fr/hal-01020926

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