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ACTIVITY REPORT

Project-Team

I4S

Statistical Inference for Structural Health Monitoring

DOMAIN

Applied Mathematics, Computation and Simulation

THEME

Optimization and control of dynamic systems

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Project-Team I4S

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1 Team members, visitors, external collaborators

Research Scientists

- Laurent Mevel [Team leader, INRIA, Senior Researcher, HDR]
- Enora Denimal [INRIA, Researcher]
- Michael Doehler [INRIA, Researcher]
- Christophe Droz [INRIA, Researcher]
- Qinghua Zhang [INRIA, Senior Researcher, HDR]

Faculty Members

- Xavier Chapeleau [UNIV GUSTAVE EIFFEL]
- Jean Dumoulin [UNIV GUSTAVE EIFFEL]
- Vincent Le Cam [UNIV GUSTAVE EIFFEL]
- Romain Noël [UNIV GUSTAVE EIFFEL]

Post-Doctoral Fellows

- Adrien Melot [INRIA, from Dec 2022]
- Boualem Merainani [UNIV GUSTAVE EIFFEL]
- Thibaud Toullier [UNIV GUSTAVE EIFFEL, ANR France Relance]
- Domenico Vizzari [UNIV GUSTAVE EIFFEL, ANR France Relance ECOTROPY]

PhD Students

- Ambroise Cadoret [IFPEN]
- Alvaro Camilo Gavilan Rojas [INRIA, from Oct 2022]
- Mira Kabbara [UNIV GUSTAVE EIFFEL, from Oct 2022]
- Arij Khaled Fawaz [UNIV GUSTAVE EIFFEL, from Oct 2022]
- Zhilei Luo [INRIA]
- Cédric Nzouatchoua [UNIV GUSTAVE EIFFEL, LAUM/IRT JULES VERNE]
- Clément Rigal [UNIV GUSTAVE EIFFEL, Université de Strasbourg/I-Cube]

Technical Staff

- Arthur Bouché [UNIV GUSTAVE EIFFEL, Engineer, from Oct 2022]
- Johann Giraudet [UNIV GUSTAVE EIFFEL, ANR France Relance]
- Ivan Gueguen [UNIV GUSTAVE EIFFEL, Technician]
- Johann Priou [INRIA, Engineer, from Feb 2022, ANR France Relance]

Interns and Apprentices

- Nathanaël Gey [UNIV GUSTAVE EIFFEL, Apprentice]
- Adji Touré [UNIV GUSTAVE EIFFEL, Apprentice, from Sep 2022]

Administrative Assistant

- Gunther Tessier [INRIA]

2 Overall objectives

2.1 In Summary

The objective of this team is the development of of robust and autonomous Structural Health Monitoring techniques by intrinsic coupling of statistics and thermo-aeroelastic modeling 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 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 that are 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 Models (FEM) 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 others) models become complex. Bridges and aircrafts are the main focus of our research. Opening our expertise on new applications topics such as helicopters and wind energy converters is also part of our priorities.

2.2 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
- To handle transient and highly varying systems under operational conditions
- To consider the impact of uncertainties on the currently 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 models, 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 very large and complex structures heavily instrumented (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)

2.3 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, i.e. 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 phenomena (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.

2.4 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 varies considerably in the range of extreme temperatures in some 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.

2.5 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 challenge for I4S's SHM projects 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 reflectometry-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.

2.6 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,

$$\begin{cases} X_{n+1} & = & AX_n + V_n \\ Y_n & = & HX_n + W_n \end{cases} \quad (1)$$

where V_n and W_n are zero mean random variables, X_n the process describing the monitored system, Y_n are the observations, A is the transition matrix of the system and H is the observation matrix between state and observation. 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 f 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 of Y_n whose length 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, water flows and other natural or man-made loads. Those variations imply a variation of the eigenproperties of the monitored structure, which need 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 should not perturb the detection. Of course, from a structural health monitoring point of view the knowledge of the true load is 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 classical mechanical equation (2)

$$M\ddot{Z} + C\dot{Z} + KZ = V \quad (2)$$

where (M, C, K) are respectively the mass, damping and stiffness matrices of the system and Z is 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 for a decade 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 $y_{-N} \dots y_{+N}$ 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 $Y_k = (y_k \dots y_{k-M}), |k| \leq P$; 2/ stack the Y_k on top of each other for $k = 0, 1, \dots, P$ to get the data matrix $\mathscr{Y}_+$ and stack the column vectors Y_k^T for $k = 0, -1, \dots, -P$ to get the data matrix $\mathscr{Y}_-$; 3/ the product $\mathscr{H} = \mathscr{Y}_+ \mathscr{Y}_-$ is a Hankel matrix. Then, matrix $\mathscr{H}$ on the one hand, and the observability matrix $\mathscr{O}(H, F)$ 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 $\mathscr{O}(H, F)$ using some Singular Value Decomposition from $\mathscr{H}$ then (H, F) from $\mathscr{O}(H, F)$ 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 automatic control literature. Up to now, there was a discrepancy between the a priori 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 models and noise. This complexity has led the mechanical community to adopt preferably frequency domain methods such as Polyreference LSCF. 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 has provided a renewed acceptance in the mechanical engineering community for the subspace algorithms. Now we focus 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 being 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 constitue 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 Rafik Zouari's PhD thesis for handling the aeroelastic effect.

3 Research program

3.1 Vibration analysis

In this section, the main features for the key monitoring issues, namely identification, detection, and diagnostic, 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 $(Z_0, \ldots, Z_N)$ is characterized by the parameter vector $\theta \in \Theta$.

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 :

$$\left\{ \begin{array}{rcl} X_{k+1} & = & F\,X_k + V_{k+1} \\ Y_k & = & H\,X_k + W_k \end{array} \right. , \tag{4}$$

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

$$\det\,(F - \lambda\,I) = 0,\;\; (F - \lambda\,I)\,\phi_\lambda = 0,\;\; \varphi_\lambda \stackrel{\Delta}{=} H\,\phi_\lambda \tag{5}$$

The (canonical) parameter vector in that case is :

$$\theta \stackrel{\Delta}{=} \begin{pmatrix} \Lambda \\ \mathrm{vec}\Phi \end{pmatrix} \tag{6}$$

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 [68].

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

$$\mathcal{H}_{p+1,q} \stackrel{\Delta}{=} \begin{pmatrix} R_1 & R_2 & \vdots & R_q \\ R_2 & R_3 & \vdots & R_{q+1} \\ \vdots & \vdots & \vdots & \vdots \\ R_{p+1} & R_{p+2} & \vdots & R_{p+q} \end{pmatrix} \stackrel{\Delta}{=} \mathrm{Hank}\,(R_i) \tag{7}$$

be the output covariance and Hankel matrices, respectively; and: $G \stackrel{\Delta}{=} \mathbf{E}\left(X_k\,Y_{k-1}^T\right)$. Direct computations of the R_i's from the equations (4) lead to the well known key factorizations :

$$R_i = HF^{i-1}G \tag{8}$$

$$\mathcal{H}_{p+1,q} = \mathcal{O}_{p+1}(H,F)\;\mathcal{C}_q(F,G) \tag{9}$$

where:

$$\mathscr{O}_{p+1}(H,F) \stackrel{\Delta}{=} \begin{pmatrix} H \\ HF \\ \vdots \\ HF^p \end{pmatrix} \quad \text{and} \quad \mathscr{C}_q(F,G) \stackrel{\Delta}{=} (G\ FG \cdots\ F^{q-1}G) \tag{10}$$

are the observability and controllability matrices, respectively. The observation matrix H is then found in the first block-row of the observability matrix $\mathscr{O}$. The state-transition matrix F is obtained from the shift invariance property of $\mathscr{O}$. The eigenstructure (λ, ϕ_λ) then results from (5).

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

3.3 Detection

Our approach to on-board detection is based on the so-called asymptotic statistical local approach. 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.

Choosing the eigenvectors of matrix F as a basis for the state space of model (4) yields the following representation of the observability matrix:

$$\mathscr{O}_{p+1}(\theta) = \begin{pmatrix} \Phi \\ \Phi\Delta \\ \vdots \\ \Phi\Delta^p \end{pmatrix} \tag{11}$$

where $\Delta \stackrel{\Delta}{=} \text{diag}(\Lambda)$, and Λ and Φ are as in (6). Whether a nominal parameter θ_0 fits a given output covariance sequence $(R_j)_j$ is characterized by:

$$\mathscr{O}_{p+1}(\theta_0) \text{ and } \mathscr{H}_{p+1,q} \text{ have the same left kernel space.} \tag{12}$$

This property can be checked as follows. From the nominal θ_0, compute $\mathscr{O}_{p+1}(\theta_0)$ using (11), and perform e.g. a singular value decomposition (SVD) of $\mathscr{O}_{p+1}(\theta_0)$ for extracting a matrix U such that

$$U^T\, U = I_s \text{ and } U^T\, \mathscr{O}_{p+1}(\theta_0) = 0. \tag{13}$$

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

$$U(\theta_0)^T\, \mathscr{H}_{p+1,q} = 0. \tag{14}$$

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

$$\widehat{\mathcal{H}}_{p+1,q} \stackrel{\Delta}{=} \text{Hank}\left(\widehat{R}_i\right), \quad \widehat{R}_i \stackrel{\Delta}{=} 1/(N-i) \sum_{k=i+1}^{N} Y_k \, Y_{k-i}^T \tag{15}$$

and to define the residual vector

$$\zeta_N(\theta_0) \stackrel{\Delta}{=} \sqrt{N}\,\text{vec}\left(U(\theta_0)^T \; \widehat{\mathcal{H}}_{p+1,q}\right). \tag{16}$$

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 (14), 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.

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.

The central limit theorem shows [62] that the residual is asymptotically Gaussian:

$$\zeta_N \xrightarrow[N\to\infty]{} \begin{cases} \mathcal{N}(0,\Sigma) & \mathbf{P}_{\theta_0}\,, \\ \\ \mathcal{N}(\mathcal{J}\,\eta,\Sigma) & \mathbf{P}_{\theta_0+\eta/\sqrt{N}}\,, \end{cases} \tag{17}$$

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 :

$$\chi^2 = \overline{\zeta}^{\,T}\, \mathbf{F}^{-1}\, \overline{\zeta} \gtrless \lambda\,, \tag{18}$$

where

$$\overline{\zeta} \stackrel{\Delta}{=} \mathcal{J}^T\, \Sigma^{-1}\, \zeta_N, \;\; \mathbf{F} \stackrel{\Delta}{=} \mathcal{J}^T\, \Sigma^{-1}\, \mathcal{J}\,. \tag{19}$$

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.

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 :

$$\chi^2_\Phi = \zeta^T \Sigma^{-1} \mathcal{J}\,\mathcal{J}_{\Phi\theta} (\mathcal{J}^T_{\Phi\theta} \mathcal{J}^T \Sigma^{-1} \mathcal{J}\,\mathcal{J}_{\Phi\theta})^{-1} \mathcal{J}^T_{\Phi\theta} \mathcal{J}^T \Sigma^{-1} \zeta \gtrless \lambda\,. \tag{20}$$

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 $\mathcal{J}_{\Phi\theta}$.

3.5 Infrared thermography and heat transfer

This section introduces the infrared radiation and its link with the temperature, in the next part different measurement methods based on that principle are presented.

3.5.1 Infrared radiation

Infrared is an electromagnetic radiation having a wavelength between 0.2 μm and 1 mm, this range begins in uv spectrum and it ends on the microwaves domain, see Figure 1.

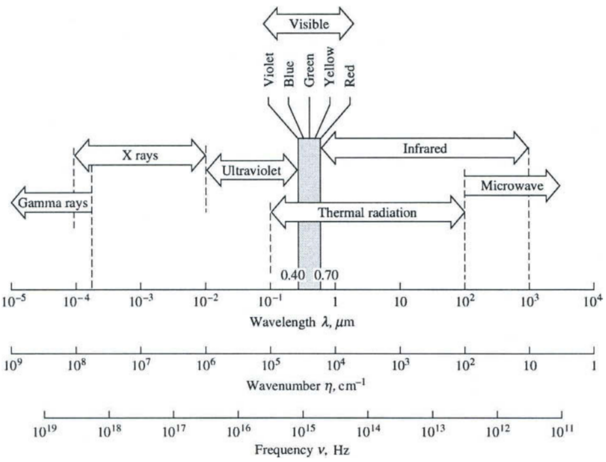

Figure 1: Electromagnetic spectrum - Credit MODEST, M.F. (1993). Radiative Heat Transfer. Academic Press.

For scientific purposes, infrared can be divided in three ranges of wavelength in which the application varies, see Table 1.

Band name	**wavelength**	**Uses \ definition**
Near infrared (PIR, IR-A, NIR)	$0.7-3\mu m$	Reflected solar heat flux
Mid infrared (MIR, IR-B)	$3-50\mu m$	Thermal infrared
Far infrared (LIR, IR-C, FIR)	$50-1000\mu m$	Astronomy

Table 1: Wavelength bands in the infrared according to ISO 20473:2007

Our work is concentrated in the mid infrared spectral band. Keep in mind that Table 1 represents the ISO 20473 division scheme, in the literature boundaries between bands can move slightly.

The Planck's law, proposed by Max Planck in 1901, allows to compute the black body emission spectrum for various temperatures (and only temperatures), see Figure 2 left. The black body is a

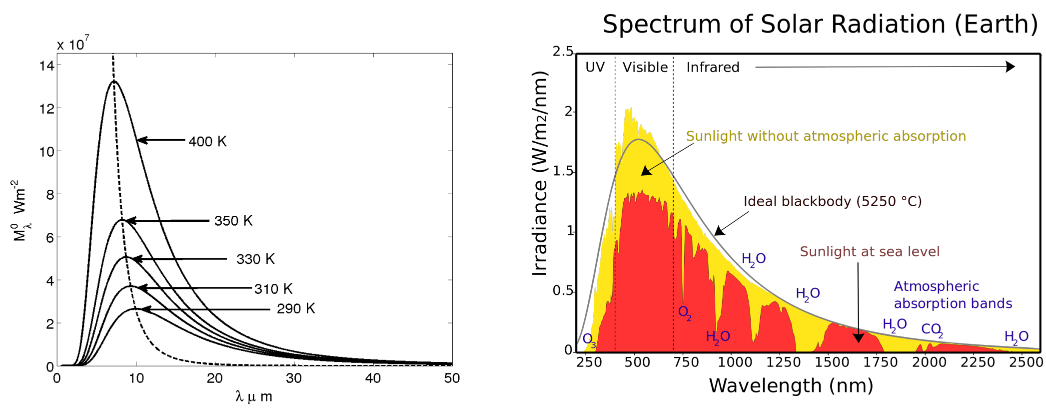

Figure 2: Left: Planck's law at various temperatures - Right: Energy spectrum of the atmosphere

theoretical construction, it represents perfect energy emitter at a given temperature, cf. Equation (21).

$$M^{o}_{\lambda,T} = \frac{C_1 \lambda^{-5}}{\exp^{\frac{C_2}{\lambda T}} - 1} \tag{21}$$

With λ the wavelength in m and T as the temperature in Kelvin. The C_1 and C_2 constants, respectively in W.m^2 and m.K are defined as follow:

$$\begin{aligned} C_1 &= 2hc^2\pi \\ C_2 &= h\frac{c}{k} \end{aligned}$$

with

- c the electromagnetic wave speed (in vacuum c is the light speed in m.s^{-1}),
- $k = 1.381e^{-23}$ J.K^{-1} the Boltzmann (Entropy definition from Ludwig Boltzmann 1873). It can be seen as a proportionality factor between the temperature and the energy of a system,
- $h \approx 6,62606957e^{-34}$ J.s the Planck constant is the link between the photons energy and their frequency.

By generalizing the Planck's law with the Stefan Boltzmann law (proposed first in 1879 and then in 1884 by Joseph Stefan and Ludwig Boltzmann), it is possible to address mathematically the energy spectrum of real body at each wavelength depending on the temperature, the optical condition and the real body properties, which is the base of the infrared thermography.

For example, Figure 2 right presents the energy spectrum of the atmosphere at various levels, it can be seen that the various properties of the atmosphere affect the spectrum at various wavelengths. Other important point is that the infrared solar heat flux can be approximated by a black body at 5523,15 K.

3.5.2 Infrared Thermography

The infrared thermography is a way to measure the thermal radiation received from a medium. With that information about the electromagnetic flux, it is possible to estimate the surface temperature of the body, see section 3.5.1. Various types of detector can assure the measure of the electromagnetic radiation.

Those different detectors can take various forms and/or manufacturing process. For our research purposes, we use uncooled infrared camera using a matrix of microbolometers detectors. A microbolometer, as a lot of transducers, converts a radiation in electric current used to represent the physical quantity (here the heat flux).

This field of activity includes the use and the improvement of vision system, like in [7].

3.6 Heat transfer theory

Once the acquisition process is done, it is useful to model the heat conduction inside the cartesian domain Ω. Note that in opaque solid medium the heat conduction is the only mode of heat transfer. Proposed by Jean Baptiste Biot in 1804 and experimentally demonstrated by Joseph Fourier in 1821, the Fourier Law describes the heat flux inside a solid

$$\varphi = k\nabla T \quad X \in \Omega \tag{22}$$

where k is the thermal conductivity in W.m^{-1}.K ^{o}, ∇ is the gradient operator and φ is the heat flux density in Wm^{-2}. This law illustrates the first principle of thermodynamic (law of conservation of energy) and implies the second principle (irreversibility of the phenomenon). From this law it can be seen that the heat flux always goes from hot area to cold area.

An energy balance with respect to the first principle yields to the expression of the heat conduction in all point of the domain Ω

$$\rho C \frac{\partial T(X,t)}{\partial t} = \nabla \cdot (k\nabla T) + P \quad X \in \Omega \tag{23}$$

with ∇.() the divergence operator, C the specific heat capacity in J.kg^{-1}.^{o}K^{-1}, ρ the volumetric mass density in kg. m^{-3}, the space variable $X = \{x, y, z\}$ and P a possible internal heat production in W.m^{-3}.

To solve the system (23), it is necessary to express the boundary conditions of the system. With the developments presented in section 3.5.1 and the Fourier's law, it is possible, for example, to express the thermal radiation and the convection phenomenon which can occur at $\partial\Omega$ the system boundaries, cf Equation (24).

$$\varphi = k\nabla T \cdot n = \underbrace{h\left(T_{fluid} - T_{Boundarie}\right)}_{\text{Convection}} + \underbrace{\epsilon\sigma_s\left(T^4_{environement} - T^4_{Boundary}\right)}_{\text{Radiation}} + \varphi_0 \quad X \in \partial\Omega \tag{24}$$

Equation (24) is the so called Robin condition on the boundary $\partial\Omega$, where n is the normal, h the convective heat transfer coefficient in W.m^{-2}.K^{-1} and φ_0 an external energy contribution W.m^{-2}, in cases where the external energy contribution is artificial and controlled we call it active thermography (spotlight etc...), otherwise it is called passive thermography (direct solar heat flux).

The systems presented in the different sections above (3.5 to 3.6) are useful to build physical models in order to represents the measured quantity. To estimate key parameters, as the conductivity, model inversion is used, the next section will introduce that principle.

3.7 Inverse model for parameter estimation

Lets take any model A which can for example represent the conductive heat transfer in a medium, the model is solved for a parameter vector P and it yields another vector b, cf Equation (25). For example if A represents the heat transfer, b can be the temperature evolution.

$$AP = b \tag{25}$$

With A a matrix of size $n \times m$, P a vector of size m and b of size n, preferentially $n \gg P$. This model is called direct model, the inverse model consist to find a vector P which satisfy the results b of the direct model. For that we need to inverse the matrix A, cf Equation (26).

$$P = A^{-1}b \tag{26}$$

Here we want to find the solution AP which is closest to the acquired measures M, Equation (27).

$$AP \approx \mathcal{M} \tag{27}$$

To do that it is important to respect the well posed condition established by Jacques Hadamard in 1902

- A solution exists.
- The solution is unique.
- The solution's behavior changes continuously with the initial conditions.

Unfortunately those condition are rarely respected in our field of study. That is why we dont solve directly the system (27) but we minimise the quadratic coast function (28) which represents the Legendre-Gauss least square algorithm for linear problems.

$$min_P\left(\|AP-\mathscr{M}\|^2\right)=min_P\left(\mathscr{F}\right) \tag{28}$$

where $\mathscr{F}$ can be a product of matrix

$$\mathscr{F}=[AP-\mathscr{M}]^T\,[AP-\mathscr{M}]$$

In some cases the problem is still ill-posed and need to be regularized for example using the Tikhonov regularization. An elegant way to minimize the cost function $\mathscr{F}$ is compute the gradient

$$\nabla\mathscr{F}(P)=2\left[-\frac{\partial AP^T}{\partial P}\right][AP-\mathscr{M}]=2J(P)^T\,[AP-\mathscr{M}] \tag{29}$$

and find where it is equal to zero, where J is the sensitivity matrix of the model A with respect to the parameter vector P.

Until now the inverse method proposed is valid only when the model A is linearly dependent of its parameter P, for the heat equation it is the case when the external heat flux has to be estimated, φ_0 in Equation (24). For all the other parameters, like the conductivity k the model is non-linearly dependant of its parameter P. For such case the use of iterative algorithm is needed, for example the Levenberg-Marquardt algorithm, cf Equation (30).

$$P^{k+1}=P^k+[(J^k)^TJ^k+\mu^k\Omega^k]^{-1}(J^k)^T\left[\mathscr{M}-A(P^k)\right] \tag{30}$$

Equation (30) is solved iteratively at each loop k. Some of our results with such linear or non linear method can be seen in [8] or [2], more specifically [1] is a custom implementation of the Levenberg-Marquardt algorithm based on the adjoint method (developed by Jacques Louis Lions in 1968) coupled to the conjugate gradient algorithm to estimate wide properties field in a medium.

3.8 Reflectometry-based methods for electrical engineering and for civil engineering

The fast development of electronic devices in modern engineering systems involves more and more connections through cables, and consequently, with an increasing number of connection failures. Wires and connectors are subject to ageing and degradation, sometimes under severe environmental conditions. In many applications, the reliability of electrical connexions is related to the quality of production or service, whereas in critical applications reliability becomes also a safety issue. It is thus important to design smart diagnosis systems able to detect connection defects in real time. This fact has motivated research projects on methods for fault diagnosis in this field. Some of these projects are based on techniques of reflectometry, which consist in injecting waves into a cable or a network and in analyzing the reflections. Depending on the injected waveforms and on the methods of analysis, various techniques of reflectometry are available. They all have the common advantage of being non destructive.

At Inria the research activities on reflectometry started within the SISYPHE EPI several years ago and now continue in the I4S EPI. Our most notable contribution in this area is a method based on the *inverse scattering* theory for the computation of *distributed characteristic impedance* along a cable from

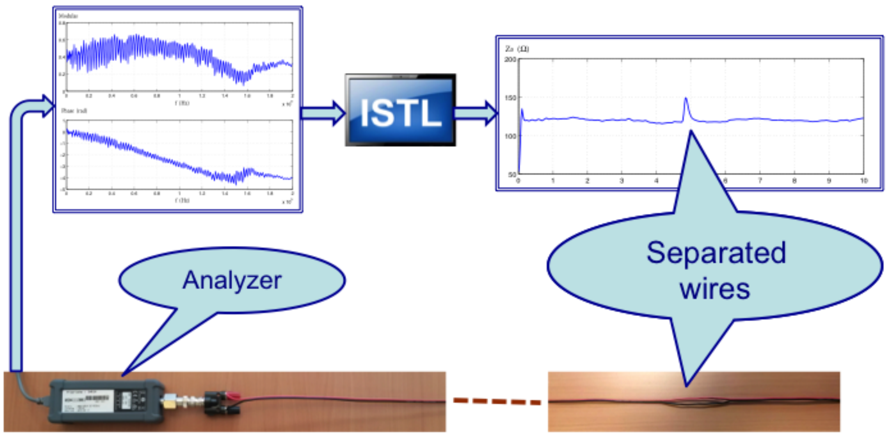

Figure 3: Inverse scattering software (ISTL) for cable soft fault diagnosis

reflectometry measurements [11, 14, 67]. It provides an efficient solution for the diagnosis of *soft* faults in electrical cables, like in the example illustrated in Figure 3. While most reflectometry methods for fault diagnosis are based on the detection and localization of impedance discontinuity, our method yielding the spatial profile of the characteristic impedance is particularly suitable for the diagnosis of soft faults *with no or weak impedance discontinuities*.

Fault diagnosis for wired networks have also been studied in Inria [65, 69]. The main results concern, on the one hand, simple star-shaped networks from measurements made at a single node, on the other hand, complex networks of arbitrary topological structure with complete node observations.

Though initially our studies on reflectometry were aiming at applications in electrical engineering, since the creation of the I4S team, we are also investigating applications in the field of civil engineering, by using electrical cables as sensors for monitoring changes in mechanical structures.

What follows is about some basic elements on mathematical equations of electric cables and networks, the main approach we follow in our study, and our future research directions.

3.8.1 Mathematical model of electric cables and networks

A cable excited by a signal generator can be characterized by the telegrapher's equations [66]

$$\frac{\partial}{\partial z}V(t,z) + L(z)\frac{\partial}{\partial t}I(t,z) + R(z)I(t,z) = 0 \tag{31}$$

$$\frac{\partial}{\partial z}I(t,z) + C(z)\frac{\partial}{\partial t}V(t,z) + G(z)V(t,z) = 0 \tag{32}$$

where t represents the time, z is the longitudinal coordinate along the cable, $V(t,z)$ and $I(t,z)$ are respectively the voltage and the current in the cable at the time instant t and at the position z, $R(z), L(z), C(z)$ and $G(z)$ denote respectively the series resistance, the inductance, the capacitance and the shunt conductance per unit length of the cable at the position z. The left end of the cable (corresponding to $z = a$) is connected to a voltage source $V_s(t)$ with internal impedance R_s. The quantities $V_s(t)$, R_s, $V(t,a)$ and $I(t,a)$ are related by

$$V(t,a) = V_s(t) - R_s I(t,a). \tag{33}$$

At the right end of the cable (corresponding to $z = b$), the cable is connected to a load of impedance R_L, such that

$$V(t,b) = R_L I(t,b). \tag{34}$$

One way for deriving the above model is to spatially discretize the cable and to characterize each small segment with 4 basic lumped parameter elements for the j-th segment: a resistance ΔR_j, an inductance ΔL_j, a capacitance ΔC_j and a conductance ΔG_j. The entire circuit is described by a system of ordinary differential equations. When the spatial discretization step size tends to zero, the limiting model leads to the telegrapher's equations.

A wired network is a set of cables connected at some nodes, where loads and sources can also be connected. Within each cable the current and voltage satisfy the telegrapher's equations, whereas at each node the current and voltage satisfy the Kirchhoff's laws, unless in case of connector failures.

3.8.2 The inverse scattering theory applied to cables

The inverse scattering transform was developed during the 1970s-1980s for the analysis of some nonlinear partial differential equations [64]. The visionary idea of applying this theory to solving the cable inverse problem goes also back to the 1980s [63]. After having completed some theoretic results directly linked to practice [14], [67], we started to successfully apply the inverse scattering theory to cable soft fault diagnosis, in collaboration with GEEPS-SUPELEC [11].

To link electric cables to the inverse scattering theory, the telegrapher's equations are transformed in a few steps to fit into a particular form studied in the inverse scattering theory. The Fourier transform is first applied to obtain a frequency domain model, the spatial coordinate z is then replaced by the propagation time

$$x(z) = \int_0^z \sqrt{L(s)C(s)}ds$$

and the frequency domain variables $V(\omega,x), I(\omega,x)$ are replaced by the pair

$$v_1(\omega,x) = \frac{1}{2}\left[Z_0^{-\frac{1}{2}}(x)U(\omega,x) - Z_0^{\frac{1}{2}}(x)I(\omega,x)\right] \tag{35a}$$

$$v_2(\omega,x) = \frac{1}{2}\left[Z_0^{-\frac{1}{2}}(x)U(\omega,x) + Z_0^{\frac{1}{2}}(x)I(\omega,x)\right] \tag{35b}$$

with the characteristic impedance

$$Z_0(x) = \sqrt{\frac{L(x)}{C(x)}}. \tag{36}$$

These transformations lead to the Zakharov-Shabat equations

$$\frac{dv_1(\omega,x)}{dx} + ikv_1(\omega,x) = q^*(x)v_1(\omega,x) + q^+(x)v_2(\omega,x) \tag{37a}$$

$$\frac{dv_2(\omega,x)}{dx} - ikv_2(\omega,x) = q^-(x)v_1(\omega,x) - q^*(x)v_2(\omega,x) \tag{37b}$$

with

$$\begin{aligned} q^\pm(x) &= -\frac{1}{4}\frac{d}{dx}\left[\ln\frac{L(x)}{C(x)}\right] \mp \frac{1}{2}\left[\frac{R(x)}{L(x)} - \frac{G(x)}{C(x)}\right] \\ &= -\frac{1}{2Z_0(x)}\frac{d}{dx}Z_0(x) \mp \frac{1}{2}\left[\frac{R(x)}{L(x)} - \frac{G(x)}{C(x)}\right] \end{aligned} \tag{38a}$$

$$q^*(x) = \frac{1}{2}\left[\frac{R(x)}{L(x)} + \frac{G(x)}{C(x)}\right]. \tag{38b}$$

These equations have been well studied in the inverse scattering theory, for the purpose of determining partly the "potential functions" $q^\pm(x)$ and $q^*(x)$ from the scattering data matrix, which turns out to correspond to the data typically collected with reflectometry instruments. For instance, it is possible to compute the function $Z_0(x)$ defined in (36), often known as the characteristic impedance, from the reflection coefficient measured at one end of the cable. Such an example is illustrated in Figure 3. Any fault affecting the characteristic impedance, like in the example of Figure 3 caused by a slight geometric deformation, can thus be efficiently detected, localized and characterized.

4 Application domains

Civil engineering:

- Vibration-based damage diagnosis
- Thermal monitoring for non-destructive evaluation
- Energy assessment of buildings
- Railway monitoring

Aeronautics:

- In-flight monitoring - flutter detection
- Ground resonance detection for helicopters

Electrical cables and networks:

- Incipient fault detection

5 Social and environmental responsibility

5.1 Impact of research results

A laboratory-size prototype of the hybrid road pavement has been made within the ANR France Relance project of Domenico Vizzari with our spinoff company ECOTROPY. The objective is energy harvesting, thanks to the exploitation of solar radiation. The innovative pavement is a multilayered structure composed by a semitransparent top layer made of glass aggregates bonded together thanks to a semi-transparent resin, an electrical layer containing the solar cells, a porous asphalt layer for the circulation of the calorific fluid, and finally, a base waterproof layer. The hybrid road can generate electricity, contrast the heat-island effect, exploit the harvested energy to run a heat pump for heating purposes, or facilitate road deicing during winter. Experimental data obtained through energetic tests are published in [28], showing that the prototype is able to harvest around 55.2 W through the heat-transfer fluid.

6 Highlights of the year

- The I4S team has organized the QIRT 2022 conference in Paris.
- Following the contract between InriaTech and Université Gustave Eiffel, I4S has delivered to SIEMENS a proof of concept of a long term thermal monitoring system with optimal heating predictive models to avoid icing on the transport infrastructure made of cement concrete and reduce energy consumption. This poof of concept is installed on the new line B of the cityval metro in Rennes.

6.1 Awards

- Christophe Droz
  - WMCV2022 Best Paper Award, for the contribution: 'Wave Transmission and Reflection Analysis Based on the 3D Second Strain Gradient Theory' co-authored by B. Yang, M. Ichchou, C. Droz and A. Zine at the 10th International Conference on Wave Mechanics and Vibrations, Lisbon, Portugal [54].

7 New results

7.1 System identification

7.1.1 Uncertainty quantification in input/output subspace system identification

Participants: Szymon Gres, Michael Doehler, Laurent Mevel.

The transfer function of a linear mechanical system can be defined in terms of the quadruplet of state-space matrices (A, B, C, D) that can be identified from input and output measurements with subspace-based system identification methods. A practical algorithm for uncertainty quantification of their estimation errors and the uncertainty of the resultant parametric transfer function is missing in the context of subspace identification. In this work, explicit expressions for the covariance related to the system matrices (B, D) are developed, and applied to the covariance estimation of the resulting transfer function. This work has been done in collaboration with Brüel&Kjær. The results have been published in [19].

7.1.2 Automated uncertainty-based extraction of modal parameters from stabilization diagrams

Participants: Johann Priou, Michael Doehler.

The interpretation of stabilization diagrams is a classical task in operational modal analysis, and has the goal to obtain the set of physical modal parameters from estimates at the different model orders of the diagram. Besides the point estimates of the modal parameters, also their confidence bounds are available with subspace identification. These uncertainties provide useful information for an automated interpretation of the stabilization diagrams. First, modes with high uncertainty are most likely non-physical modes. Second, the confidence bounds provide a natural threshold for the automated extraction of modal alignments, avoiding the requirement of a deterministic threshold regarding the allowable variation within an alignment. In this work, a strategy is presented for the automated mode extraction considering their uncertainties, based on clustering a statistical distance measures between the modes. This work has been done in collaboration with ETH Zurich and Sercel, and has been published in [52].

7.1.3 Uncertainty propagation in subspace methods for operational modal analysis under misspecified model orders

Participants: Szymon Gres, Michael Doehler.

The quantification of statistical uncertainty in modal parameter estimates has become a standard tool, used in applications to, e.g., damage diagnosis, reliability analysis, modal tracking and model calibration. Although efficient multi-order algorithms to obtain the (co)variance of the modal parameter estimates with subspace methods have been proposed in the past, the effect of a misspecified model order on the uncertainty estimates has not been investigated. In fact, the covariance estimates may be inaccurate due to the presence of small singular values in the supposed signal space. In this work we go back to the roots of the uncertainty propagation in subspace methods and revise it to account for the case when a part of the noise space is erroneously added to the signal space. This work has been done in collaboration with ETH Zurich, and has been published in [46].

7.1.4 Identification of wind turbines

Participants: Ambroise Cadoret, Enora Denimal, Laurent Mevel.

Operational wind turbines and rotating machines in general show a time periodic behavior, which does not agree with the usual assumptions of the Operational Modal Analysis (OMA) methods developed for civil engineering, where time invariant systems are considered. The existing OMA methods for rotating systems are based on pre-processing of the data to adapt to the classical identification methods. However, these methods have strong limitations and are based on strict assumptions such as the isotropy of the rotor, making difficult their application to a real case. To overcome these limitations, in this work, based on the Floquet theory, it is proposed to approximate the dynamical behavior of the periodic systems as being invariant. Thus, the classical identification methods can be safely used to retrieve the parametric signature of the periodic systems. This approach is validated on an aero-servo-elastic numerical model of a rotating 10MW wind turbine. Secondly, it is shown that the identified modes can be used for fault detection, with the detection of the rotor anisotropy using the identified mode shapes. Results have been published in [34, 35, 36, 56]

7.2 Damage monitoring of civil engineering structures/fault detection and isolation

7.2.1 Damage detection with uncertainties in reference

Participants: Eva Viefhues, Michael Doehler, Laurent Mevel.

The statistical subspace-based damage detection technique has shown promising theoretical and practical results for vibration-based structural health monitoring. Ideally, the reference model is assumed to be perfectly known without any uncertainty, which is not a realistic assumption in practice. Indeed, the left null space of a reference output covariance Hankel matrix is usually estimated from data to avoid model errors in the residual computation. Then, the associated uncertainties may be non-negligible, in particular when the available reference data is of limited length. In this work, it is investigated how the statistical distribution of the residual is affected when the reference null space is estimated. The asymptotic residual distribution is derived, where its refined covariance term considers also the uncertainty related to the reference null space estimate. The associated damage detection test closes a theoretical gap for real-world applications and leads to increased robustness of the method in practice. This work has been done in collaboration with BAM, Germany. The work has been published in [27].

7.2.2 Sensor placement with optimal damage detectability for statistical damage detection

Participants: Alexander Mendler, Michael Doehler.

Damage diagnosis based on global structural vibrations critically depends on the sensor layout, in particular when a small number of sensors is used for large structures under unknown excitation. This work proposes a sensor placement strategy that yields an optimized sensor layout with maximum damage detectability in selected structural components. The optimization criterion is based on the Fisher information of the design parameters of those structural components, such as material constants or cross-sectional values. It is evaluated using a finite element model, and considers the statistical uncertainties of the damage-sensitive feature. The methodology can be applied to any damage-sensitive feature whose distribution can be approximated as Gaussian. Since the Fisher information is defined component-wise, the sensor layout can be tuned to become more sensitive to damage in local structural components, such as damage hotspots, non-inspectable components, or components that are critical for the safety and serviceability of the structure. This work has been done in collaboration with University of British Columbia, Canada. The work has been published in [22].

7.2.3 Probability of detection curves for reliability analysis of damage detection methods

Participants: Michael Doehler.

For any structural monitoring project it is required to select relevant measurement quantities and damage-sensitive features are selected, but very few systematic approaches exist in the literature on how to select the most appropriate features. The presented work fills this gap and develops an approach based on probability of detection (POD) curves. The POD curves are generated based on a novel method for statistical damage detection tests that requires a finite element model and vibration data from the undamaged structure. The approach explicitly considers the uncertainties in the features due to unknown loads, measurement noise, and short measurement durations. Although global damage-sensitive features are considered, such as modal parameters and subspace-based residuals, the detectability is evaluated for local structural components, as well as for changes in parameters related to boundary conditions like changes in prestress or support conditions. This work has been done in collaboration with Technical University of Munich, Germany, and has been published in [48], [49] and [50].

7.2.4 Kalman predictor subspace residual for mechanical system damage detection

Participants: Michael Doehler, Qinghua Zhang, Laurent Mevel.

For mechanical system structural health monitoring, a new residual generation method is proposed in this work, inspired by a recent result on subspace system identification. It improves statistical properties of the existing subspace residual, which has been naturally derived from the standard subspace system identification method. Replacing the monitored system state-space model by the Kalman filter one-step ahead predictor is the key element of the improvement in statistical properties, as originally proposed by Verhaegen and Hansson in the design of a new subspace system identification method. This work has been published in [44].

7.3 Analysis and monitoring of non-stationary systems

7.3.1 Set-membership estimation based on ellipsoid bundles for discrete-time LPV descriptor systems

Participants: Qinghua Zhang.

This work considers set-membership estimation for discrete-time linear parameter-varying descriptor systems. Ellipsoid bundle, a new set representation tool combining certain characteristics of ellipsoids and zonotopes, is used to design a setmembership estimation method for the considered systems. We use the $L\infty$ technique to design the estimator parameters in order to optimize estimation accuracy. The stability problem of the proposed method is studied and an offline sufficient stability condition is established. This work has been done in collaboration with Dalian University of Technology and Harbin Institute of Technology, China. The work has been published in [26].

7.3.2 Adaptive Observer with Enhanced Gain to Address Deficient Excitation

Participants: Qinghua Zhang.

For joint estimation of state variables and unknown parameters, adaptive observers usually assume some persistent excitation (PE) condition. In practice, the PE condition may not be satisfied, because the underlying recursive estimation problem is ill-posed. To remedy the lack of PE condition, inspired by the ridge regression, this work proposes a regularized adaptive observer with enhanced parameter adaptation gain. Like in typical ill-posed inverse problems, regularization implies an estimation bias, which can be reduced by using prior knowledge about the unknown parameters. This work has been done in collaboration with Normandie Université, and is published in [55].

7.3.3 Strain-based joint damage estimation robust to unknown non-stationary input force

Participants: Laurent Mevel.

To avert catastrophic failure in the structures, joints are typically designed to yield, but not fail, so that energy accumulated under cyclic loading is dissipated. Eventually, this renders the structural joints to be characteristically weaker and more vulnerable than the members. Yet, damage detection research mostly assumes damage in the members only. This work proposes a model-based predictor-corrector algorithm that uses an interacting filtering approach to efficiently estimate joint damage in the presence of input and measurement uncertainties. For the predictor model, a novel strain-displacement relationship specific to semi-rigid frames is developed to map nodal displacements to corresponding strain measurements. The proposed estimation method embeds robustness against non-stationary input (e.g. seismic excitation) in the state filter, itself. The modified state filter (robust Kalman filter) runs within an enveloping parameter filter (Particle filter) to simultaneously estimate the system states and joint damage parameters, respectively, using the response signal. This work has been done in collaboration with the Indian Institute of Technology Mandi. The work has been published in [15].

7.3.4 Switching Kalman filter for damage estimation in the presence of sensor faults

Participants: Laurent Mevel.

Sensor faults are inevitable during real field SHM in which sensor may malfunction or get detached from the structural surface, registering completely irrelevant information as measurement. Eventually, such erroneous information induce error in the estimation which leads to an inaccurate, sometimes divergent and impractical solution. This work deals with Bayesian filtering based structural damage detection in the presence of one or multiple (consecutive) sensor faults. The damage detection is addressed with joint state-parameter estimation while a switching filtering strategy is employed for sensor fault detection. Switching approach employs multiple possible sensor fault models which are subsequently integrated to the measurement model of the joint estimation approach. It has been demonstrated that estimation of health for structures measured with faulty sensors can actually lead to a false (positive and negative) alarm which can, however, be avoided by the employment of the proposed approach. This work has been done in collaboration with the Indian Institute of Technology Mandi. The work has been published in [16].

7.3.5 Damage detection in tensegrity structures using interacting Particle-Ensemble Kalman Filter

Participants: Laurent Mevel.

Tensegrities are structural mechanisms, with dedicated compression (struts/bars) and tension members (cables). Under external load, tensegrity may change its form by altering its member pre-stress, thereby affecting its global stiffness even in the absence of damage. Moreover, tensegrities can have different stiffness properties under the same structural configuration in the absence of any damage or external load, if the pre-stress levels of the members are different. However, the changes in dynamic characteristics of tensegrities are not limited to the aforementioned causes only and is also affected by ambient uncertainties. A variation in temperature may alter the dynamic characteristics of a tensegrity by influencing its material (Young's modulus, etc.) and structural (boundary conditions, structural dimensions, etc.) properties. The present work develops a vibration-based time-domain approach for tensegrity health monitoring in the presence of uncertainties due to ambient force, measurement noise, and varying temperature. An interacting filtering technique has been used, where the state variables are estimated by the Ensemble Kalman filter that resides inside the Particle filter which computes the health parameters. Furthermore, for large tensegrities that require excessive computation, only a substructure can be investigated explicitly. Yet the integration of substructures within predictor-corrector model-based SHM algorithms needs special investigation from consistency, stability, and accuracy perspectives. The need for interface measurement has been circumvented through an output injection approach. This work has been done in collaboration with the Indian Institute of Technology Mandi, and has been published in [31] and [32].

7.4 Exploiting complex physical models for structural design, analysis and monitoring

7.4.1 Reliable crack detection in a rotor system with uncertainties via advanced simulation models based on kriging and Polynomial Chaos Expansion

Participants: Enora Denimal.

In this work the nonlinear effects induced by the presence of a transverse crack are considered to carry out vibratory monitoring and detect transverse cracks in rotating systems subject to model uncertainties. More precisely, we focus more particularly on the global complexity of the nonlinear dynamic behaviour of cracked rotors and the evolution of their harmonic components as a function of the parameters of a transverse breathing crack (its position and depth) when numerous uncertainties are considered. These random uncertainties correspond to random geometric imperfections (two disc thicknesses), random material properties (Young modulus and material density) and boundary conditions uncertainty (two bearing stiffnesses). The objective of the present work is to identify robust indicators capable of determining the presence of a crack and its status even though numerous uncertainties are present. To conduct such a study, an advanced surrogate modelling technique based on kriging and Polynomial Chaos Expansion (PCE) is proposed for the prediction of both the critical speeds and the harmonic components during passage through sub-critical resonances. The work is in collaboration with Ecole Centrale Lyon, and has been published in [23] and presented in [42] and [58].

7.4.2 Topology optimisation of friction under-platform dampers using Moving Morphable Components and the Efficient Global Optimization algorithm

Participants: Enora Denimal.

Underplatform dampers (UPDs) are traditionally used in aircraft engines to reduce the risk of high cycle fatigue. By introducing friction in the system, vibrations at resonance are damped. However, UDPs are also the source of nonlinear behaviours making the analysis and the design of such components complex. The shape of such friction dampers has a substantial impact on the damping performances, topology optimisation is seldomly utilised-particularly for nonlinear structures. In the present work, we present a numerical approach to optimise the topology of friction dampers in order to minimise the vibration amplitude at a resonance peak. The proposed approach is based on the Moving Morphable Components framework to parametrise the damper topology, and the Efficient Global Optimisation algorithm is employed for the optimisation. The results demonstrate the relevance of such an approach for the optimisation of nonlinear vibrations in the presence of friction. New efficient damper geometries are identified in a few iterations of the algorithm, illustrating the efficiency of the approach. More generally, the different geometries are analysed and tools for clustering are proposed. The results show how topology optimisation can be employed for nonlinear vibrations to identify efficient layouts for components. The work is in collaboration with Imperial College and Rolls Royce (UK), has been published in [18] and presented at [40] and [57].

7.4.3 Geometric design of friction ring dampers in blisks using nonlinear modal analysis and Kriging surrogate model

Participants: Enora Denimal.

Integrally bladed disks (blisk) have been widely used in the turbo-machinery industry due to its high aerodynamic performance and structural efficiency. A friction ring damper (FRD) is usually integrated in the system to improve its low damping. However, the design of the geometry of this FRD become complex and computationally expensive due to the strong nonlinearities from friction interfaces. In this work, we propose an efficient modelling strategy based on advanced nonlinear modal analysis and Kriging surrogate models to design and optimize the geometry of a 3D FRD attached to a high fidelity full-scale blisk. The 3D ring damper is parametrised with a few key geometrical parameters. The impact of each geometric parameter and their sensitivities to nonlinear dynamic response can be efficiently assessed using Kriging meta-modelling based on a few damped nonlinear normal modes. Results demonstrate that the damping performances of ring dampers can be substantially optimized through the proposed modelling strategy whilst key insights for the design of the rings are given. It is also demonstrated that the distribution of the contact normal load on the contact interfaces has a strong influence on the damping performances and can be effectively tuned via the upper surface geometry of the ring dampers. The work is in collaboration with Imperial College and Strathclyde University (UK), and has been published in [25].

7.4.4 Topological optimisation and 3D printing of a Bladed disc

Participants: Enora Denimal.

Bladed discs are a major component in turbomachinery, pushed to their limits to meet more stringent specifications to increase their performances. Structural topology optimisation allows to improve substantially the mechanical properties while drastically reducing the mass. With the coming of additive manufacturing, optimised geometry can be manufactured making this technology even more attractive. In this work, the topology of a full 3D-Finite Element Model of an academic bladed disc is optimised to improve its dynamic performances in terms of mass, stress and modal coincidences; and experimental validation is expected. First, the disc is designed to fit in the test-rig and the mechanical integrity of the 3D-printed disc is experimentally verified. Second, the topology of the blades is optimised based on a density-based approach. A methodology is proposed to perform topology optimisation for a full bladed disc and to formulate the optimisation problem. Thus, adding a static force at the blade tip forces a better material distribution over the domain and increases the blade stiffness. To minimise the number of coincidences, a numerical strategy based on iterative topology optimisation simulations is proposed to identify the correct set of frequential constraints. The work is in collaboration with Imperial College and is published in [33].

7.4.5 Two-dimensional periodic structures modeling based on second strain gradient elasticity for a beam grid

Participants: Christophe Droz.

Higher order gradient elasticity theories are widely applied to determine the wave propagation characteristics of microsized structures. The novelty of this work is the use of the Second Strain Gradient (SSG) theory to explore the mechanism of a micro-sized 2D beam grid. The strong formulas of continuum model including governing equations and boundary conditions are derived by using the Hamilton principle. Then, a valuable long-range Lattice Spring Model (LSM) is elaborated, providing a reasonable explanation for the model based on SSG theory. The dynamic continuum equations from LSM are computed through the Fourier series transform approach. Finally, the dynamic properties of 2D beam grid are analyzed within the Wave Finite Element Method (WFEM) framework. The band structure and slowness surfaces, confined to the irreducible first Brillouin zone, are studied in frequency spectrum. The energy flow vector fields and wave beaming effects are discussed through SSG theory and Classical Theory (CT) of elasticity. The results show that the proposed approach is of significant potential for investigating the 2D wave propagation characteristics of complex micro-sized periodic structures. The work is in collaboration with Ecole Centrale Lyon, and has been published in [30] and [54].

7.4.6 Machine Learning-Driven Surrogates for Sound Transmission Loss Simulations

Participants: Christophe Droz.

Surrogate models are data-based approximations of computationally expensive simulations that enable efficient exploration of the model's design space and informed decision making in many physical domains. The usage of surrogate models in the vibroacoustic domain, however, is challenging due to the non-smooth, complex behavior of wave phenomena. This work investigates four machine learning (ML) approaches in the modelling of surrogates of sound transmission loss (STL). Feature importance and feature engineering are used to improve the models' accuracy while increasing their interpretability and physical consistency. The transfer of the proposed techniques to other problems in the vibroacoustic domain and possible limitations of the models are discussed. Experiments show that neural network surrogates with physics-guided features have better accuracy than other ML models across different STL models. Furthermore, sensitivity analysis methods are used to assess how physically coherent the analyzed surrogates are. The work is in collaboration with Ecole Centrale Lyon and has been published in [17] and [38].

7.4.7 Simulation of the FDA nozzle benchmark: A lattice Boltzmann study

Participants: Romain Noël.

Contrary to flows in small intracranial vessels, many blood flow configurations such as those found in aortic vessels and aneurysms involve larger Reynolds numbers and, therefore, transitional or turbulent conditions. Dealing with such systems require both robust and efficient numerical methods. We assess here the performance of a lattice Boltzmann solver with full Hermite expansion of the equilibrium and central Hermite moments collision operator at higher Reynolds numbers, especially for under-resolved simulations. To that end the food and drug administration's benchmark nozzle is considered at three different Reynolds numbers covering all regimes: 1) laminar at a Reynolds number of 500, 2) transitional at a Reynolds number of 3500, and 3) low-level turbulence at a Reynolds number of 6500. The lattice Boltzmann results are compared with previously published inter-laboratory experimental data obtained by particle image velocimetry. Our results show good agreement with the experimental measurements throughout the nozzle, demonstrating the good performance of the solver even in under-resolved simulations. In this manner, fast but sufficiently accurate numerical predictions can be achieved for flow configurations of practical interest regarding medical applications. The work is in collaboration with University of Magdeburg (Germany) and ETH Zurich (Switzerland), and has been published in [20].

7.4.8 DIARITSup: a framework to supervise live measurements, Digital Twins models computations and predictions for structures monitoring

Participants: Jean Dumoulin, Thibaud Toullier.

DIARITsup is a chain of various softwares following the concept of "system of systems". It interconnects hardware and software layers dedicated to in-situ monitoring of structures or critical components. It embeds data assimilation capabilities combined with specific Physical or Statistical models like inverse thermal and/or mechanical ones up to the predictive ones. It aims at extracting and providing key parameters of interest for decision making tools. Its framework natively integrates data collection from local sources but also from external systems. DIARITsup is a milestone in our roadmap for SHM Digital Twins research framework. Furthermore, it intends providing some useful information for maintenance operations not only for surveyed targets but also for deployed sensors. The work has been published in [59].

7.5 Exploiting new sensor technologies for structural analysis and monitoring

7.5.1 Use of high spatial resolution distributed optical fiber to monitor the crack propagation of an adhesively bonded joint during ENF and DCB tests

Participants: Quentin Sourisseau, Xavier Chapeleau.

Similarly to other industrial areas, there is a strong interest for the use of bonded FRP (Fiber Reinforced Polymers) repair or reinforcement for steel structures in the case of offshore applications. However, the reliability of the adhesively bonded (FRP) shall stand as high as steel renewal, this requires additional developments, in particular, a complete understanding of the repair mechanical strength which depends on material and interfacial properties. Fracture mechanics is an interesting approach to assess the risk to undergo interlaminar fracture or steel to adhesive interfacial disbonding failure. This work proposes crack front monitoring by a distributed optical fiber as an alternative to the standard techniques. Firstly, the issues related to the use of continuous optical fiber are raised (insertion, precision resolution, measurement noise, exploitation methodologies). Then, experimental investigations on ENF and DCB tests are presented and analyzed using the proposed methodology to monitor crack propagation using the optical fiber strain measurement. The results show that an optical fiber bonded on the surface of the sample can be used to measure and follow the crack propagation during the test which simplifies and adds precision to the standardize critical toughness computation method. The work is in collaboration with Bureau Veritas, and has been published in [24] and [53].

7.5.2 Durability of Fiber Optic Sensors for Distributed Strain Measurements in Concrete Structures

Participants: Xavier Chapeleau.

The durability of the bonded Distributed Optical Fiber Sensor (DOFS) instrumentation is investigated to assess possible alteration of its performance over aging, which would raise questions about the validity of strain measurements in the long term. In this work, steel rebars were equipped with bonded optical fibers. Half-length of the instrumented rebars was subjected to hydrothermal ageing by immersion in an alkaline solution, while the remaining length was exposed to standard laboratory conditions. After exposure, the rebars were tested in tension and the DOFS strain profiles were simultaneously measured. These strain profiles were then compared to reference measurements performed before ageing, providing insights on the influence of the ageing conditions on the response of the DOFS. This work is in collaboration with Cerema and Andra, and has been published in [39].

7.5.3 Strain transfer modeling of distributed optical fiber sensors

Participants: Xavier Chapeleau.

To prevent damage during installation and monitoring in harsh environments, the optical fiber or cable used for distributed strain measurements are always surrounded by one or several stacks of coatings made of different materials. As consequence, a mechanical strain transfer occurs. This means that a strain lag exists between the strain in the core of the optical and the one at outer of the optical fiber/cable that is sought to be measured. The strain transfer occurs on small distance (typically few centimeters). As consequence, it affects only the strain profiles measured by high-resolution distributed strain sensing systems such as the one based on the measurement of the Rayleigh back-scattering by OFDR (Optical Frequency Domain Reflectomer). In the presence of high strain gradients such as those induced by the presence of a singularity (crack) or by a particular geometry or heterogeneous assembly of different materials, the strain transfer can lead to misinterpretation of the high-resolution strain distributed measurements. A general solution describing the strain transfer for any arbitrary strain distribution is introduced in this work. This work has been published in [37].

7.5.4 Quadratic Interpolation of Image Cross-Correlation for Subpixel Motion Extraction

Participants: Bian Xiong, Qinghua Zhang.

Digital image correlation techniques are well known for motion extraction from video images. Following a two-stage approach, the pixel-level displacement is first estimated by maximizing the cross-correlation between two images, then the estimation is refined in the vicinity of the cross-correlation peak. Among existing subpixel refinement methods, quadratic surface fitting (QSF) provides good performances in terms of accuracy and computational burden. It estimates subpixel displacement by interpolating cross-correlation values with a quadratic surface. By means of counterexamples, it is shown in this work that, contrary to a widespread intuition, the quadratic surface fitted to the pixel-level cross-correlation values in the neighborhood of the cross-correlation peak does not always have a maximum. The main contribution then consists in establishing the mathematical conditions ensuring the existence of a maximum of this fitted quadratic surface, based on a rigorous analysis. Algorithm modifications for handling the failure cases of the QSF method are also proposed, in order to consolidate it for subpixel motion extraction. This work has been published in [29].

7.5.5 Thermal Behavior of a Novel Solar Hybrid Road for Energy Harvesting

Participants: Domenico Vizzari, Jean Dumoulin.

Transportation is undergoing a radical transformation toward a novel way of thinking about road pavement: a sustainable, multifunctional infrastructure able to satisfy mobility needs, ensuring high safety standards, low carbon impact, automated detection through smart sensors, and resilience against natural and anthropogenic hazards. In this scenario, the road could also play a role for energy harvesting, thanks to the exploitation of solar radiation. The latter can be directly converted into electricity by solar cells placed under a semitransparent layer, or it can be harvested through a calorific flowing fluid. The aim of this work is to introduce the concept of "hybrid road," which is able to exploit both approaches. The innovative pavement is a multilayered structure composed by a semitransparent top layer made of glass aggregates bonded together thanks to a semitransparent resin, an electrical layer containing the solar cells, a porous asphalt layer for the circulation of the calorific fluid, and finally, a base waterproof layer. The hybrid road can generate electricity, contrast the heat-island effect, exploit the harvested energy to run a heat pump for heating purposes, or facilitate road deicing during winter. The present work details experimental data obtained through energetic tests performed with a laboratory-size prototype of the hybrid road. The results show that the prototype is able to harvest around 55.2 W through the heat-transfer fluid. Furthermore, the heat exchange between water and asphalt has a cooling effect on the entire prototype. This work has been published in [28].

7.5.6 Instrumentation architectures and measurements post-processing approaches for Infrared thermography applied to thermal monitoring in outdoor conditions

Participants: Jean Dumoulin, Thibaud Toullier, Laurent Mevel.

Technological progress in uncooled infrared focal plane array sensors has contributed significantly to enlarge the scope of applications of such sensing technique in many domains: Leisure, Manufacturing, Process Survey, Building insulation diagnostic, Civil Engineering, Road works, etc. Different outdoor situations and objects of interest monitored by an in-house designed measurement architecture are presented. Designed instrumentation architectures and measurements correction from varying environmental conditions and geometrical considerations are discussed. A first step toward joint estimation of emissivity and temperature is introduced for outdoor applications. Then moving object detection by an AI approach applied on thermal image sequences is also presented and discussed. This work has been published in [45].

7.5.7 Self-powered communicating wireless sensor with flexible aero-piezoelectric energy harvester

Participants: Vincent Le Cam.

This work presents an ultra-flexible piezoelectric air flow energy harvester capable of powering a wireless sensor. The method to easily adapt the aero-electric generator to the wind is presented. In the wind tunnel, different configurations have been tested to determine the best one for energy harvesting at low wind speed. In particular, the galloping configuration, with the addition of a bluff body at the free end of the cantilever which allows to improve the performance of the micro-generator by coupling the vibrations induced by the vortices and the galloping phenomena. The effects of mechanical and electrical coupling of several generators on the performance of energy harvesting are presented. The harvested energy was then used to operate a wireless sensor. This work has been in collaboration with IETR, and has been published in [21].

8 Bilateral contracts and grants with industry

8.1 Bilateral contracts with industry

SNCF: Hot boxes detection

Participants: Jean Dumoulin, Thibaud Toullier, Boualem Merainani.

The main strategic issue is the maintenance in operational condition of the Hot Box Detectors (DBC). The removal of the DBC from the track is part of Tech4Rail's ambition: reducing equipment to the track. The innovation aimed at in this project is to study and develop a measurement solution to be deployed at the edge of a lane out of danger zone and independent of track equipment. Among the scientific obstacles identified are the following three:

- the behavior of the measurement system in deteriorated meteorological conditions in a real site,

- the design and implementation of an automated prototype for in-situ deployment (connection to an existing announcement system, hardware packaging of the system, study and design of a scalable software solution allowing pre-processing data),
- the development of automatic processing tools for the analysis of massive data generated by in-situ measurement systems.

Siemens: Proof of concept monitoring coupled with prediction model for de-icing metro lane surface

Participants: Jean Dumoulin, Thibaud Toullier.

A proof of concept study aims at combining real site monitoring solutions with adjoint state FE thermal model approach to predict optimal heating required to preserve surface from icing in winter conditions. Furthermore, we introduced in our prediction model connection with in-line weather forecast provided by Meteo France Geoservice at different time horizons and spatial scales. Total amount: 124 k€.

Bureau Veritas: Bonded repairs for offshore structures

Participants: Xavier Chapeleau, Quentin Sourisseau.

The maintenance of offshore steel structure is a great challenge. Vessels and mobile offshore units can be maintained and repaired onshore in shipyards but, fixed units, such as platforms or FPSO (Floating Production, Storage and Offloading) structures, do not come back in dry dock and shall be maintained at sea. Mostly willing in harsh offshore environment (like tropical areas), these structures are prone to the corrosion due to high temperature and high humidity conditions. To repair them, the development of new technologies based on bonding processes are interesting alternatives to the common crop and renew repair technics. In the JIP Strength Bond Offshore project launched by Bureau Veritas Marine and Offshore (BV) in March 2019 with the partners Total, Petrobras, Naval Group, Siemens, Infra-core and Coldpad, a composite patch is developed. The project aims to achieve the following main objectives:

- Enable a better evaluation of the margin between the actual strength of a repair and the design load,
- Validate the characterization procedure for strength prediction of bonded assembly,
- Define a robust strength prediction method,
- Standardize the qualification process for offshore composite bonded repairs.

In this project involving the laboratories UGE/MAST/SMC and UGE/COSYS/SII-I4S, the PhD student (Quentin Sourisseau) studied new approaches for the design assessment of bonded reinforcements on steel structures. These approaches were based on the use of innovative monitoring systems during fracture mechanics standardized tests (DCB for mode I loading, ENF for mode II and MMB for mixed mode) for the characterization to feed numerical design tools based on cohesive zone modelling for strength analysis. The Digital Image Correlation (DIC) was used to obtained directly the cohesive laws using the J-integral evaluation while the critical toughness was calculated from the measurement of the crack length obtained with Distributed Fiber Optic Sensors (DOFS). These parameters, the cohesive laws and the critical toughness were integrated in different modelling strategies based on finite element method. The developed methodologies were then applied to real-scale samples in order to verify their predictive capacities. Experimental results were compared to numerical predictions and to an alternative approach from the literature relying on the use of a coupled stress-energy criteria. It was conclude that the approach based of the cohesive zone modelling gave the most accurate results in the prediction in terms of mechanical behavior (strain and stress) and in terms of failure load.

Date of Phd thesis defense: 21/10/2022

Sercel: Vibration monitoring

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

With the goal of providing a complete SHM system for vibration monitoring with their high-end sensors, we have transferred modal analysis and damage detection algorithms in a technology transfer in two contracts to Sercel, involving technical development and support (2020-2022). Amount for I4S: 15k€. Besides the transfer, an ANR France Relance project with Sercel has started in 2022. Furthermore, several meetings with Sercel have happened to define joint future work, with the objective to launch a "contrat cadre" for research on SHM applications.

9 Partnerships and cooperations

9.1 International initiatives

9.1.1 Participation in other International Programs

BayFrance

Participants: Michael Doehler.

This mobility project with Technical University of Munich (TUM) for mutual research stays in Bavaria and France (2022–2023) is funded by the Bavarian Ministry of Science and French Ministry of Foreign Affairs, with the objective to initiate research cooperation. In this project, the goal is to develop reliability assessment strategies for SHM and NDT methods, and to aim at European fundings.

UNYFI: RSE Saltire Facilitation Workshop Awards

Participants: Enora Denimal.

The project UNYFI (2022 – 2023) has been funded by the Royal Society of Edinburgh (RSE) between Strathclyde University and the I4S team to engage an international collaboration and initiate a research project to develop a European network and aim for European fundings.

ASTI

Participants: Jean Dumoulin, Laurent Mevel, Michael Doehler.

The joint lab ASTI between Inria, University Gustave Eiffel and CNR has been approved and the letters of intent have been signed by all partners. The kick off meeting of this collaborating tri-party research lab has been postponed due to COVID.

Collaboration with Imperial College London

Participants: Enora Denimal.

E. Denimal collaborates with Imperial College London on the topic of structural optimisation for non-linear vibrations. She is a visiting researcher in the Dynamics group, has co-supervied and is currently co-supervising Msc students:

- MSc: Daniel Wickens, Imperial College London, 3D printing and test of topologicaly optimised blades, E. Denimal and L. Renson, 09/2021-06/2022.
- MSc: Jeremy Videau, Imperial College London, 3D printing and experimental validation of topologicaly optimal UPD, E. Denimal and L. Renson, 09/2021-06/2022.
- MSc: Adam Hu, Imperial College London, Powder-based damping of aero-engine blades, E. Denimal and L. Renson, 09/2022-09/2023.

Internal fundings have been secured to perform 3D printing and experimental validation of numerical works. Applications for larger calls and for the creation of an associate team are in progress.

Collaboration with IIT Mandi

Participants: Laurent Mevel.

L. Mevel is directing the thesis of Neha Aswal with S. Sen at IIT Mandi. The subject is the structural health monitoring of tensegrity structures.

9.2 International research visitors

9.2.1 Visits of international scientists

Other international visits to the team

Jie Yuan

Status: Lecturer

Institution of origin: University of Strathclyde

Country: United Kingdom

Dates: 25-28/11/2022

Context of the visit: collaboration on uncertainty quantification in structural nonlinear dynamics

Mobility program/type of mobility: research stay with RSE Saltire Awards UNYFI

Alexander Mendler

Status: post-Doc

Institution of origin: Technical University of Munich (TUM), Chair of Non-Destructive Testing

Country: Germany

Dates: 18/07–30/07/2022, 03/10–15/10/2022

Context of the visit: collaboration on reliability assessment of SHM/NDT methods with M. Doehler

Mobility program/type of mobility: research stay with BayFrance mobility project

Szymon Greś

Status: post-Doc

Institution of origin: ETH Zurich

Country: Switzerland

Dates: 22/11–29/11/2022

Context of the visit: collaboration on system identification methods with M. Doehler and L. Mevel

Mobility program/type of mobility: research stay

9.2.2 Visits to international teams

Research stays abroad

Enora Denimal

Visited institution: Imperial College London

Country: United Kingdom

Dates: 11-15/07/2022 and 14-16/09/2022

Context of the visit: collaboration on uncertainty propagation for structural nonlinear dynamics

Mobility program/type of mobility: research stay

Jean Dumoulin

Visited institution: University of Shanghai for Science and Technology

Country: China

Dates: 01/06/2022 – 31/05/2023 (duration of program)

Context of the visit: Research collaboration on new building wall to reduce heat wave effects, teaching on basic of infrared thermography for thermal monitoring and non destructive testing. This work is carried out in the College of Energy and Power Engineering.

Mobility program/type of mobility: visiting professor program with several stays in China (Nota: Due to COVID restriction the program is held online)

9.3 European initiatives

9.3.1 H2020 projects

DESDEMONA (DEtection of Steel Defects by Enhanced MONitoring and Automated procedure for self-inspection and maintenance)

Participants: Jean Dumoulin, Laurent Mevel, Michael Doehler, Xavier Chapeleau, Qinghua Zhang, Boualem Merainani, Thibaud Toullier, Bian Xiong.

- Call: RFCS-2017 (Call of the research programme of the Research Fund for Coal and Steel - 2017)
- Type of Action: RFCS-RPJ (Research project)

- Objective: DESDEMONA aim is the development of novel design methods, systems, procedures and technical solutions to integrate sensing and automation technologies for the purpose of self-inspection and self-monitoring of steel structures.
- Duration: 2018–2022
- Coordinator: Pr. Vincenzo Gatulli (La Sapienza University of Rome)
- Academic and industrial Partners: Sapienza Università di Roma (Italy), Universidad de Castilla – La Mancha, (Spain), Universidade do Porto (Portugal), Università di Pisa (Italy), UGE (France), Aiviewgroup srl (Italy), Sixense systems (France), Ecisa compania general de construcciones sa (Spain), Università di Cassino e del Lazio Meridionale (Italy), Universidad de Alicante (Spain), Inria (France).
- Inria contact: J. Dumoulin and L. Mevel
- Abstract: DESDEMONA objective is the development of novel design methods, systems, procedure and technical solution, to integrate sensing and automation technologies for the purpose of self-inspection and self-monitoring of steel structures. The approach will lead to an increment of the service life of existing and new steel civil and industrial infrastructure and to a decrease in the cost associated to inspections, improving human activities performed in difficult conditions, safety and workers' potential by the use of advanced tools. The research aims to expand beyond the current state-of-the-art new high-quality standard and practices for steel structure inspection and maintenance through the interrelated development of the following actions: i) steel structure geometry and condition virtualization through data fusion of image processing, thermography and vibration measurements; ii) developing a procedure for steel defect detection by robotic and automatic systems such as Unmanned Aerial Vehicles (UAV) and ground mobile robots iii) embedding sensor systems to revalorize and transform steel elements and structures into self-diagnostic (smart) elements and materials even through nanotechnologies, iv) realizing an experimental lab-based apparatus and a series of case studies inspected by intelligent and robotic systems. The project outcome will have an impact on the reduction of the cost of steel structures inspection and maintenance and on the increase of user safety and comfort in industrial and civil environment. The proposal with a multidisciplinary approach fulfils the objectives of the Strategic Research Agenda of the European Steel Technology Platform.

Collaboration within the H2020 LIVE-I project

Participants: Christophe Droz.

C. Droz collaborates with Ecole Centrale de Lyon (France) and Compredict (Germany), through the co-supervision of a PhD student on the topic of multi-objective optimisation and digital twin for the design of lightweight transmissions.

- Date/duration: 2020-2023
- Partners: Ecole Centrale de Lyon, Compredict.
- Abstract: The European Industrial doctorate LIVE-I (Lightening and Innovating transmission for improving Vehicle Environmental Impacts) is a MSCA-ITN project, part of the Horizon 2020 programme and aims to design lightweight gear transmissions. The main objective of LIVE-I is to demonstrate a significant weight reduction of gearboxes using advanced modeling tools together with advanced materials and systems. The efficiency improvements of gear transmissions will be adressed by introducing new paradigms in the design of components, using meta-materials, studying the robustness of a given optimization with respect to real manufacturing conditions, developing smart concepts in accordance with vibroacoustic comfort.

9.3.2 Other european programs/initiatives

ERA-NET MarTERA Flow-Cam

Participants: Qinghua Zhang.

- Date/duration: 2020-2023
- Project partners: CEA LIST (coordinator), UGE, DESISTEK, TEKNOPAR, MEDYSYS.
- Abstract: The FLoating Offshore Wind turbine CAble Monitoring project aims at studying new methods for the inspection, detection and monitoring of structural defects in the interconnection system of floating offshore wind farms. Based on multi-physics models linking damage mechanisms of conductive wires to electrical and thermal properties, new structural health monitoring methods studied in the project involve multi-sensor data processing and an underwater remotely operated vehicle.

9.4 National initiatives

IFPEN

Participants: Laurent Mevel, Enora Denimal.

Collaboration with IFPEN leading to the thesis of A. Cadoret on applying OMA techniques on wind turbines.

CEA List ONDULA2

Participants: Vincent Le Cam.

With CEA-LIST and Alstom-Rail, this project (until June 2022) focuses on NDT ultrasonic testing methods for rails. The goal is to deploy several complete rail-sensors in real railway application test benches; another aspect consists in transferring the common knowledge to the final customer Alstom. A daughter board for high frequency ultrasonic emission/reception has been successfully developed and licensed in three industrial transfers.

MTE DGITM CASC: Acoustic Wave for Wirebreak in cables Monitoring

Participants: Vincent Le Cam.

This governmental project aims at testing new algorithms in the CASC platform for detecting and localizing wire breaks in cables of suspension bridges by means of acoustic waves time difference of arrival (TDOA), with the objective to provide a better "time of arrival" time-stamping (by means of the maximmum of likelihood for instance). Another objective is the implementation of a good time-synchronization in wireless sensors while keeping the GPS-energy lower as possible. This was done in the context of the PhD of D. Pallier. A demonstration of acoustic sensors for bridge cable monitoring has been set up, and works for qualification carried out. The project has been prolonged until 2023.

ANR SCaNING

Participants: Vincent Le Cam.

- Duration: 2021 – 2024
- Partners: UGE (Coordinator), Université de Toulouse, Aix-Marseille Université, Université de Bordeaux, Andra, EDF
- Inria contact: Vincent Le Cam
- Abstract: Using embedded sensors which will provide information similar to that used in NDE while allowing to continuously evaluate performance indicators (compressive strength and Young's modulus) and the concrete conditions (porosity and water content) to improve indicator reliability and optimize diagnosis and communicating sensors through fully autonomous, low-power networks makes it possible to consider systems with low installation and operation costs. The project is lead by MAST LAMES laboratory of UGE. The full instrumentation part is ensured by I4S common team.

ANR Convinces

Participants: Jean Dumoulin, Romain Noël.

- Duration: 11/2021 – 10/2025
- Partners: Univ. Lorraine (coordinator), CERTES (UPEC), Univ. Strasbourg, UGE, Cerema.
- Abstract: The ANR project CONVINCES is investigating the influence of convection in suspensions of micro-encapsulated phase change material (mPCM) in urban civil engineering applications. This project will include LBM (Lattice Boltzmann Method) and DEM (Discrete Element Method) in multi-scale simulations plus series of experiments at different scales to study the thermal impact of such mPCM suspensions in porous media. The final objective is the thermal regulation of pavements.

ANR RESBIOBAT

Participants: Jean Dumoulin.

- Duration: 01/2022 – 12/2025
- Partners: UGE (coordinator), CERTES (UPEC), LNE, CSTB, Cerema, Themacs Ingénierie.
- Abstract: The ANR project RESBIOBAT addresses energy and environmental issues. Major advances are expected in the building sector. Reliable in-situ thermal characterization of buildings before and after a renovation action are required. Moreover, construction must be more "sustainable", notably by using bio-sourced materials and raw earth. In this project, we propose an inter-disciplinary technical solution combining modeling, simulations and measurements for a better in-situ evaluation of the energy performances of conventional and sustainable walls. The identification of the thermal characteristics will be performed by an inverse method combining a hygro-thermal model solved in real time by a "reduced bases" technique and sensors selected by "optimal experimental design". After a robustness study via virtual tests, a prototype will be realized and tested on real walls in laboratory and in the Equipment of Excellence Sense-City.

ANR France Relance: Sercel

Participants: Johann Priou, Michael Doehler, Laurent Mevel.

- Duration: 02/2022 – 01/2024
- Partner: Sercel
- Abstract: The objectives of this Action 4 France Relance project are the development of automated and robust algorithms for operational modal analysis under environmental variations.

ANR France Relance: Ecotropy

Participants: Thibaud Toullier, Jean Dumoulin.

- Duration: 09/2022 – 08/2024
- Partner: Ecotropy
- Abstract: Two research and development actions in Artificial intelligence making the best use of existing and future databases are explored:
  - Study and development of a decision support tool with a powerful model giving consumption indicators of a building or infrastructure from a set of data (weather, energy, typologies, etc.),
  - Study and Development of a model by AI approach capable of classifying situations of alert or acceptability of energy consumption.

ANR France Relance: Ecotropy

Participants: Domenico Vizzari, Jean Dumoulin.

- Duration: 01/2022 – 12/2023
- Partner: Ecotropy
- Abstract: Two research and development actions are explored:
  - Data assimilation for control: cross-referencing of data (weather health, energy) to develop management strategies that are robust to the uncertainties inherent in environmental data predictions.
  - Control in a context of uncertainty: the objective is the automation of the mechanisms for predicting heating needs in a building or on a roadway at a controllable surface temperature.

ANR France Relance: SDEL-CC Vinci

Participants: Johann Giraudet, Vincent Le Cam.

- Duration: 10/2021 – 09/2023
- Partner: SDEL-CC Vinci
- Abstract: The objectives of this Action 1 France Relance project are industrial transfer for better performance in the "lightning localization" system for monitoring of high voltage lines. New algorithms enable the detection of other defects than lightnings like short-circuit and disphasing.

PIA4: MINERVE

Participants: Vincent Le Cam.

- Duration: 2022–2027
- 22 partners, coordinator: SNCF. Budget: 40 M€, 743 k€ for the team
- Title: Méthodes et outils pour la collaboration sectorielle et la continuité numériuqe sur le cycle de vie (MINERVE)
- Abstract: The six main objectives of the MINERVE project are: - Develop design and construction methods and tools using effective BIM approaches for each business - Anticipate and optimize the construction phase, based on sustainable BIM (digital continuity, frugality of models) - Developing digital twins (exploring the potential of AI for decision support), using opportunities with regard to biodiversity and the environment - Use the digital twin to improve resilience to climate change - Develop an industrializable, standardized and shared vision of interfaces ensuring digital continuity via the BIM model on all phases - Build a collaborative ecosystem around the modeling of linear and particularly railway infrastructure

  The team participates with BIM and monitoring of railway structures by modeling vibrations, defining original ways of operational monitoring including fiber optic sensors.

PIA4: DIAM

Participants: Vincent Le Cam.

- Duration: 2022–2026
- Partners: STIMIO (coordinator), SNIC, UGE. Budget: 3 M€, 693 k€ for the team.
- Abstract: In this project, new ways to diagnose infrastructure deterioration are identified through the use of innovative instrumentation and by merging different data sources. With focus on railway monitoring, the goal is online diagnosis communication of critical trackside elements, and to enrich trackside elements with augmented infrastructure monitoring systems. New algorithms and models for predictive maintenance are developed.

9.5 Regional initiatives

AIS Rennes

Participants: Enora Denimal.

The city of Rennes has allocated 10k€ to E. Denimal to facilitate her installation and engage collaborations (2021–2023).

AIS Rennes

Participants: Christophe Droz.

The city of Rennes has allocated 10k€ to C. Droz to facilitate his installation and engage collaborations (2022–2024).

PULSAR jeunes chercheurs Pays de la Loire

Participants: Romain Noël.

The region Pays de la Loire, has allocated 48k€ to R. Noël to his project on numerical simulations of phase change material for thermal regulation of cities (2022–2024).

10 Dissemination

10.1 Promoting scientific activities

10.1.1 Scientific events: organisation

General chair, scientific chair

- Jean Dumoulin was general chair of QIRT 2022, Paris.

Member of the organizing committees

- Jean Dumoulin, Christophe Droz, Laurent Mevel and Thibaud Toullier were member of the organizing committee of QIRT 2022, Paris.

10.1.2 Scientific events: selection

Chair of conference program committees

- Vincent Le Cam
  - head and general secretary of the EWSHM scientific committee
  - co-chair of SHM@COFREND and member of its scientific committee: each year a *SHM by Cofrend day* is organized grouping around 100 leaders in France in SHM techniques

Member of the conference program committees

- Jean Dumoulin
  - member of the scientific committee of the GI Division (Geosciences Instrumentation and Data Systems) of EGU (European Geosciences Union) for infrastructure instrumentation and monitoring since 2013
  - member of the scientific committee of QIRT (quantitative Infrared Thermography) since 2014
  - co-chair of session GI2.2 Data fusion, integration, correlation and advances of non-destructive testing methods and numerical developments for engineering and geosciences applications at EGU 2022
  - co-chair of session 5: Components, Modeling, and Theory in IR Remote Sensing in the CONFERENCE (OP421): Infrared Remote Sensing and Instrumentation XXX at SPIE Optics + Photonics 2022
- Qinghua Zhang
  - member of the IFAC Symposium on Fault Detection, Supervision and Safety for Technical Processes (SAFEPROCESS) 2022 scientific committee
  - member of the IFAC Workshop on Adaptive and Learning Control Systems (ALCOS) 2022 scientific committee

  - member of IFAC Technical Committee on Modelling, Identification and Signal Processing (TC 1.1)
  - member of IFAC Technical Committee on Adaptive and Learning Systems (TC 1.2)
  - member of IFAC Technical Committee on Fault Detection, Supervision and Safety of Technical Processes (TC 6.4)
- Laurent Mevel
  - member of the EWSHM scientific committee
  - member of the SHMII scientific committee
- Vincent Le Cam
  - member of the IWSHM scientific committee
  - member of the Asian Pacific Workshop scientific committee
- Michael Doehler
  - member of IFAC Technical Committee on Modelling, Identification, and Signal Processing (TC 1.1) since 2017
  - member of the IOMAC scientific committee since 2018
  - member of the SHM@COFREND scientific committee since 2021
  - member of the EWSHM scientific committee since 2022
  - organizer of special session on uncertainty quantification at IOMAC 2022
- Christophe Droz
  - chair of session PER3 Periodic structures and metamaterials at ISMA 2022
  - chair of Keynote 1 and Session 2-4 'Modelling' at QIRT 2022

Reviewer

- Michael Doehler was reviewer for SAFEPROCESS 2022, CDC 2022.
- Jean Dumoulin was reviewer for QIRT 2022, EGU 2022.
- Qinghua Zhang was reviewer for CDC 2022, ALCOS 2022, SAFEPROCESS 2022.
- Laurent Mevel was reviewer for SAFEPROCESS 2022.
- Vincent Le Cam was reviewer for EWSHM 2022.
- Enora Denimal was reviewer for ASME TurboExpo 2022.

10.1.3 Journal

Member of the editorial boards

- Jean Dumoulin is member of the editorial board of the journal Quantitative Infrared Thermography, and Executive Editor for the journal Geoscientific Instrumentation and Data Systems.
- Laurent Mevel is member of the editorial board of the journal of Mechanical Systems and Signal Processing, the journal Mathematical Problems in Engineering, and of the journal Shock and Vibration.
- Enora Denimal is guest editor for special issues in applied mechanics and in the ASME Journal of Risk and Uncertainty in Engineering Systems : Part B.
- Christophe Droz is member of the editorial board of Applied Acoustics section in Frontiers in Acoustics and is topic editor for Frontiers in Mechanical Engineering.

Reviewer - reviewing activities

- Laurent Mevel was reviewer for Mechanical Systems and Signal Processing, Structural Control and Health Monitoring and Journal of Sound and Vibration.
- Michael Doehler was reviewer for Mechanical Systems and Signal Processing, Engineering Structures, Structural Control and Health Monitoring, Journal of Sound and Vibration, Journal of Risk and Uncertainty in Engineering Systems Part A: Civil Engineering
- Jean Dumoulin was reviewer for Building and Environment, SPIE Optical Engineering, GI Journal (EGU), QIRT Journal.
- Enora Denimal was reviewer for Mechanical Systems and Signal Processing, Journal of Engineering for Gas Turbines and Power, Machines, Journal of Zhejiang University-Science A, Sustainability, Mechanics Based Design of Structures and Machines, Applied Sciences.
- Romain Noël was reviewer for Aerospace, Applied Sciences, International Journal of Environmental Research and Public Health, Numerical Algorithms, Physics of Fluids.
- Christophe Droz was reviewer for Mechanical Systems and Signal Processing, Journal of Sound and Vibration, The Journal of the Acoustical Society of America - Express Letters, Applied Sciences, Mathematics, Aerospace.
- Xavier Chapeleau was reviewer for the journals Structural Control & Health Monitoring, Journal of Marine Science and Engineering.
- Qinghua Zhang was reviewer for IEEE Transactions on Automatic Control, Automatica.

10.1.4 Invited talks

- Michael Doehler gave an invited talk at ETH Zurich, Switzerland, at the Structural Mechanics and Monitoring Chair, and at KU Leuven, Belgium, at the Department of Civil Engineering. He was also invited to give an overview talk on uncertainty quantification at IOMAC 2022, Vancouver [43].
- Enora Denimal gave an invited talk at Inria Saclay to the PLATON team on the topic of uncertainty quantification and structural optimisation for structural nonlinear vibrations.
- Vincent Le Cam gave a conference keynote at RNGR "Rencontres Nationales des Gestionnaires Routiers", title: "Technologies avancées de surveillance des défauts courants des ouvrages d'art"; and gave the introduction keynote on the 4th SHM@COFREND day, title: "La démarche de structuration nationale du SHM".
- Jean Dumoulin gave an invited talk at SPIE Optics and Photonics conference [45].

10.1.5 Research administration

- Laurent Mevel
  - deputy head of science of Inria Rennes
  - member of Comité de centre in Rennes
  - member of CLHSCT committee in Rennes
  - member of Commisision d'Evaluation at Inria
- Vincent Le Cam
  - head of SII lab at Université Gustave Eiffel in Nantes
  - deputy co-head of COSYS department at Université Gustave Eiffel
  - member of the scientific council of WEN (West Electronic Network) since 2014, which is a cluster of about 200 companies, academics and research laboratories active in electronics
- Jean Dumoulin
  - deputy head of SII lab at Université Gustave Eiffel in Nantes

10.2 Teaching - Supervision - Juries

10.2.1 Teaching

- Jean Dumoulin
  - Licence Professionnelle TAM (Techniques Avancées en Maintenance): thermographie infrarouge active, 30h, Université Paris-Est Créteil (UPEC), France
  - Master 2 ITII, BTP, module Maintenance et réhabilitation des ouvrages, Transferts thermiques dans les Structures : Des principes physiques à l'application sur site réel, 12 h, Ecole Centrale de Nantes (ECN), France.
  - Master 2 and PhD in College of Energy and Power Engineering, from Radiative heat transfer toward basic of Infrared Thermography (8h), University of Shanghai for Science and Technology (USST), China.
- Vincent Le Cam
  - I3, ESEO, 32h, practical lessons on embedded and smart systems under Linux, France
  - Master Electrical Engineering (GEII), 3h CM in M1, 4h CM in M2 on electronic systems and Structural Monitoring, Université Bretagne Sud, Lorient, France
  - M2 ENSIM Le Mans, 5h CM (monitoring des structures par capteurs sans fils)
  - EC Nantes, 32h TP (electronique embarquée, Linux et drivers)
  - One-week program for visit of bachelor students BEST, l'ESIEE-Paris on campus of UGE Nantes: electronique, instrumentation et signal processing
- Xavier Chapeleau
  - Licence Pro Mesures physiques, Mesures optiques, 15h, IUT de St Nazaire, Université de Nantes, France
- Romain Noël
  - Master 2, plenary conference on Fluid Mechanics Applications (2h), École des Mines de Saint-Étienne, France
  - Master 1, Advanced Fluid Mecanics, Lectures (2x3h) + practical lessons (2x3h), École des Mines de Saint-Étienne, France
- Enora Denimal
  - Licence 3, Introduction to the use of numerical tools in research (10h), Ecole Normale Supérieure de Rennes, filière mécatronique
  - Cycle préparatoire intégré INSA Rennes, STPI: TP découverte des mécanismes (8h), TD mécanique générale (24h), Projet hydraulique et résistance des matériaux (28h).
  - Suivi d'un apprenti en cycle Ingénierie Mécanique de l'INSA Rennes (10heqTD/an).

10.2.2 Supervision

PhD students

- Ambroise Cadoret, *Couplage d'un modèle numérique d'éolienne avec un algorithme de type « Operational Modal Analysis » (OMA)*, L. Mevel, Ecole doctorale MathSTIC, since 10/2020.
- Quentin Sourisseau, *Evaluation de stratégies de dimensionnement de renforcements composites collés sur structures métalliques offshore*, Phd thesis director: S. Chataigner (UGE/MAST), Phd thesis co-supervisors X. Chapeleau and E. Leprête (UGE/MAST), Ecole doctorale SPI, defense 10/2022.

- Cédric Nzouatchoua, *Apport des réseaux de capteurs à ultrasons sans-fil dans la surveilllance de l'état de santé des structures composites*, M. Bentahar, V. Le Cam and N. Collin , Ecole doctorale SPI, since 11/2020.
- Zhilei Luo, *Vision-based vibration analysis*, Q. Zhang and M. Doehler, Ecole doctorale MathSTIC, since 11/2021
- Clément Rigal, *Modélisation multi-échelle d'écoulements convectifs avec des matériaux à changement de phase micro-encapsulés à travers un milieu poreux*, Y. Hoarau , R. Noël and J.Dumoulin, Ecole doctorale MSTII, since 12/2021
- Mira Kabbara, *Modélisation et caractérisation de capteurs à fibre optique continus*, Q. Zhang, F. Bourquin, X. Chapeleau, Ecole doctorale Matisse, since 10/2022
- Arij Khaled Fawaz, *Etude de l'évolution des lois cohésives d'interface en mode II pour un assemblage collé sous charge en milieu marin*, S. Chataigner, E. Lepretre, X. Chapeleau, Ecole doctorale SIS, since 10/2022
- Alvaro-Camilo Gavilan-Rojas, *Reduced order models for non-destructive evaluation of periodic structures*, C. Droz and Q. Zhang, Ecole doctorale MathSTIC, since 10/2022
- Barbara Zaparoli Cunha, *Lightweight transmission design through multi-objective optimisations and digital twins*, C. Droz, M. Ichchou, M. Zine, Ecole doctorale MEGA, since 11/2020
- Neha Aswal, *structural health monitoring for tensegrity structures*, L. Mevel and S. Sen, IIT Mandi, since 2020.

Postdocs and research engineers

- Boualem Merainani, postdoc funded by SNCF then european Project KDT JU BRIGHTER , supervised by J. Dumoulin, 09/2021-12/2023
- Thibaud Toullier, postdoc funded by Siemens, then ANR France Relance with ECOTROPY, supervised by J. Dumoulin, 09/2022-08/2024
- Domenico Vizzari, postdoc ANR France Relance with ECOTROPY, supervised by J. Dumoulin, 01/2022-12/2023
- Adrien Melot, postdoc Action Exploratoire Inria, supervised by E. Denimal, 12/2022-12/2024.
- Johann Giraudet, research engineer ANR France Relance with SDEL-CC vinci, supervised by V. Le Cam, 10/2021-09/2023
- Johann Priou, research engineer ANR France Relance with Sercel, supervised by M. Doehler, 02/2022-01/2024

Internships

- M1: Samuel Fruchard, Coupled evolutionary algorithm for 3D topology optimisation in vibrationsc, supervised by E. Denimal, 04/2022 - 08/2022
- M1: Paul Le Gouvello, Modelling of the Tabarly bridge dampers, supervised by E. Denimal and R. Noël, 04/2022 - 08/2022.
- M1: Arnaud Ridard, Numerical simulations of thermal porous flow with LBM, supervised by R. Noël and C. Rigal, 05/2022 - 08/2022
- M2: Alexis Renier-Robin, Image anisotropic dithering by LBM, supervised by R. Noël, 10/2021 - 02/2022
- M2: Alexis Renier-Robin, Synthetic Aperture Radar Deformations Interpolation using Neural Networks, supervised by J. Dumoulin, 04/2022 - 09/2022

10.2.3 Juries

- Enora Denimal
  - PhD Defense - Examinator - Ecole Centrale de Lyon. Adrien Melot, “Dynamique non-linéaire des transmissions par engrenages - application aux pompes à vide de type roots”. Defense May 11, 2022.
  - PhD Defense - Examinator - Université Polytechnique des Haut de France. Yassine El Attaoui, “Modélisation des surfaces réelles de contact et de leur évolution : Intégration dans les simulations de crissement”. Defense July 6, 2022.
  - PhD Defense - Examinator - Ecole Centrale de Lyon. Matthias Cousté , “Prise en compte de contraintes du procédé d’assemblage dans l’optimisation d’une caisse automobile”. Defense December 14, 2022.
- Christophe Droz
  - PhD Defense Examinator - Ecole Centrale de Lyon. Bo Yang, "Wave motion in elastic enriched Medias based on the second strain gradient formulation". Defense May 9th 2022.
- Qinghua Zhang
  - PhD Defense Examinator - Université de Caen Normandie. Manon Lailler, "Synthèse d’observateurs pour des systèmes fini- et infini- dimensionnels retardés". Defense September 5th 2022.

10.3 Popularization

10.3.1 Internal or external Inria responsibilities

- Christophe Droz
  - Co-organizator of the Sci-Rennes seminar series at the Inria center of the University of Rennes (since Sep. 2022).

10.3.2 Interventions

- Enora Denimal participated at the event "Rencontres maths, jeunes filles et chercheuses" of the Séphora Berrebi Association on June 27, 2022.
- Participation of R. Noël, D. Vizzari and T. Toullier to the Fête de la Science from the 14/10/2022 to 16/10/2022 with a stand about the impact of new pavements on urban climate.

11 Scientific production

11.1 Major publications

[1] J. Brouns, A. Crinière, J. Dumoulin, A. Nassiopoulos and F. Bourquin. ‘Diagnostic de structures de Génie Civil : Identification des propriétés spatiales et de la surface d’un défaut’. In: *SFT 2014*. Société Française de Thermique. Lyon, France, May 2014. URL: https://hal.inria.fr/hal-01082184.

[2] A. Crinière, J. Dumoulin, C. Ibarra-Castanedo and X. Maldague. ‘Inverse model for defect characterisation of externally glued CFRP on reinforced concrete structures: comparative study of square pulsed and pulsed thermography’. In: *Quantitative InfraRed Thermography Journal* 11.1 (Mar. 2014), pp. 84–114. DOI: 10.1080/17686733.2014.897512. URL: https://hal.archives-ouvertes.fr/hal-01081174.

[3] M. Döhler and L. Mevel. ‘Efficient Multi-Order Uncertainty Computation for Stochastic Subspace Identification’. In: *Mechanical Systems and Signal Processing* 38.2 (June 2013), pp. 346–366.

[4] M. Döhler and L. Mevel. ‘Fast Multi-Order Computation of System Matrices in Subspace-Based System Identification’. In: *Control Engineering Practice* 20.9 (Sept. 2012), pp. 882–894.

[5] M. Döhler and L. Mevel. 'Modular Subspace-Based System Identification from Multi-Setup Measurements'. In: *IEEE Transactions on Automatic Control* 57.11 (Nov. 2012), pp. 2951–2956.

[6] M. Döhler and L. Mevel. 'Subspace-based fault detection robust to changes in the noise covariances'. In: *Automatica* 49.9 (Sept. 2013), pp. 2734–2743. DOI: 10.1016/j.automatica.2013.06.019. URL: https://hal.inria.fr/hal-00907662.

[7] J. Dumoulin and V. Boucher. 'Infrared thermography system for transport infrastructures survey with inline local atmospheric parameter measurements and offline model for radiation attenuation evaluations'. In: *Journal of Applied Remote Sensing* 8.1 (2014), pp. 084978–084978.

[8] J. Dumoulin, A. Crinière and R. Averty. 'The detection and thermal characterization of the inner structure of the 'Musmeci' bridge deck by infrared thermography monitoring'. In: *Journal of Geophysics and Engineering* 10.6 (Dec. 2013), p. 17. DOI: 10.1088/1742-2132/10/6/064003. URL: https://hal.inria.fr/hal-01081320.

[9] A. Jhinaoui, L. Mevel and J. Morlier. 'A new SSI algorithm for LPTV systems: application to a hinged-bladed helicopter'. In: *Mechanical Systems and Signal Processing* 42.1 (Jan. 2014), pp. 152–166.

[10] N. Le Touz, T. Toullier and J. Dumoulin. 'Study of an optimal heating command law for structures with non-negligible thermal inertia in varying outdoor conditions'. In: *Smart Structures and Systems* 27.2 (2021), pp. 379–386. DOI: 10.12989/sss.2021.27.2.379. URL: https://hal.inria.fr/hal-03145348.

[11] F. Loete, Q. Zhang and M. Sorine. 'Experimental validation of the inverse scattering method for distributed characteristic impedance estimation'. In: *IEEE Transactions on Antennas and Propagation* 63.6 (2015), p. 7. DOI: 10.1109/TAP.2015.2417215. URL: https://hal.inria.fr/hal-01231807.

[12] L. Marin, M. Döhler, D. Bernal and L. Mevel. 'Robust statistical damage localization with stochastic load vectors'. In: *Structural Control and Health Monitoring* 22.3 (Mar. 2015).

[13] M. Zghal, L. Mevel and P. Del Moral. 'Modal parameter estimation using interacting Kalman filter'. In: *Mechanical Systems and Signal Processing* 47.1 (Aug. 2014), pp. 139–150.

[14] Q. Zhang, M. Sorine and M. Admane. 'Inverse Scattering for Soft Fault Diagnosis in Electric Transmission Lines'. In: *IEEE Transactions on Antennas and Propagation* 59.1 (2011), pp. 141–148. URL: https://hal.inria.fr/inria-00365991.

11.2 Publications of the year

International journals

[15] N. Aswal, S. Sen and L. Mevel. 'Strain-based joint damage estimation approach robust to unknown non-stationary input force'. In: *Structural Control and Health Monitoring* 29.10 (13th Sept. 2022), pp. 1–29. DOI: 10.1002/stc.2999. URL: https://hal.inria.fr/hal-03843210.

[16] N. Aswal, S. Sen and L. Mevel. 'Switching Kalman filter for damage estimation in the presence of sensor faults'. In: *Mechanical Systems and Signal Processing* 175 (Aug. 2022), p. 109116. DOI: 10.1016/j.ymssp.2022.109116. URL: https://hal.inria.fr/hal-03772742.

[17] B. Z. Cunha, A. Zine, M. Ichchou, C. Droz and S. Foulard. 'On Machine Learning-Driven Surrogates for Sound Transmission Loss Simulations'. In: *Applied Sciences* (23rd Oct. 2022). DOI: 10.3390/app122110727. URL: https://hal.archives-ouvertes.fr/hal-03639282.

[18] E. Denimal, L. Renson, C. Wong and L. Salles. 'Topology optimisation of friction under-platform dampers using Moving Morphable Components and the Efficient Global Optimization algorithm'. In: *Structural and Multidisciplinary Optimization* (24th Jan. 2022), pp. 1–24. DOI: 10.1007/s00158-021-03158-w. URL: https://hal.inria.fr/hal-03655578.

[19] S. Gres, M. Döhler, N.-J. Jacobsen and L. Mevel. 'Uncertainty quantification of input matrices and transfer function in input/output subspace system identification'. In: *Mechanical Systems and Signal Processing* 167 (1st Mar. 2022), pp. 1–17. DOI: 10.1016/j.ymssp.2021.108581. URL: https://hal.inria.fr/hal-03607852.

[20] F. Huang, R. Noël, P. Berg and S. A. Hosseini. 'Simulation of the FDA nozzle benchmark: A lattice Boltzmann study'. In: *Computer Methods and Programs in Biomedicine* 221 (June 2022), p. 106863. DOI: 10.1016/j.cmpb.2022.106863. URL: https://hal.inria.fr/hal-03881693.

[21] J. Le Scornec, B. Guiffard, R. Seveno, V. Le Cam and S. Ginestar. 'Self-powered communicating wireless sensor with flexible aero-piezoelectric energy harvester'. In: *Renewable Energy* 184 (Jan. 2022), pp. 551–563. DOI: 10.1016/j.renene.2021.11.113. URL: https://hal.inria.fr/hal-03908995.

[22] A. Mendler, M. Döhler and C. E. Ventura. 'Sensor placement with optimal damage detectability for statistical damage detection'. In: *Mechanical Systems and Signal Processing* 170 (May 2022), pp. 1–15. DOI: 10.1016/j.ymssp.2021.108767. URL: https://hal.inria.fr/hal-03699103.

[23] J.-J. Sinou and E. Denimal. 'Reliable crack detection in a rotor system with uncertainties via advanced simulation models based on kriging and Polynomial Chaos Expansion'. In: *European Journal of Mechanics - A/Solids* 92 (Mar. 2022), pp. 1–18. DOI: 10.1016/j.euromechsol.2021.104451. URL: https://hal.archives-ouvertes.fr/hal-03425672.

[24] Q. Sourisseau, E. Leprêtre, S. Chataigner, X. Chapeleau, L. Mouton and S. Paboeuf. 'Use of high spatial resolution distributed optical fiber to monitor the crack propagation of an adhesively bonded joint during ENF and DCB tests'. In: *International Journal of Adhesion and Adhesives* 115 (June 2022), pp. 1–20. DOI: 10.1016/j.ijadhadh.2022.103124. URL: https://hal.inria.fr/hal-03699099.

[25] Y. Sun, E. Denimal, J. Yuan and L. Salles. 'Geometric design of friction ring dampers in blisks using nonlinear modal analysis and Kriging surrogate model'. In: *Structural and Multidisciplinary Optimization* 65.3 (Mar. 2022), p. 98. DOI: 10.1007/s00158-021-03093-w. URL: https://hal.inria.fr/hal-03591512.

[26] W. Tang, Q. Zhang, Z. Wang and Y. Shen. 'Set-membership estimation based on ellipsoid bundles for discrete-time LPV descriptor systems'. In: *Automatica* 145 (1st Nov. 2022), pp. 1–11. DOI: 10.1016/j.automatica.2022.110580. URL: https://hal.inria.fr/hal-03850355.

[27] E. Viefhues, M. Döhler, F. Hille and L. Mevel. 'Statistical subspace-based damage detection with estimated reference'. In: *Mechanical Systems and Signal Processing* 164 (Feb. 2022), p. 108241. DOI: 10.1016/j.ymssp.2021.108241. URL: https://hal.inria.fr/hal-03607818.

[28] D. Vizzari, J. Dumoulin, E. Chailleux, E. Gennesseaux, S. Lavaud, S. Bouron and J.-L. Manceau. 'Thermal Behavior of a Novel Solar Hybrid Road for Energy Harvesting'. In: *Journal of Testing and Evaluation* 51.4 (14th Nov. 2022), p. 20220283. DOI: 10.1520/JTE20220283. URL: https://hal.inria.fr/hal-03895819.

[29] B. Xiong, Q. Zhang and V. Baltazart. 'On Quadratic Interpolation of Image Cross-Correlation for Subpixel Motion Extraction'. In: *Sensors* 22.3 (Feb. 2022), p. 1274. DOI: 10.3390/s22031274. URL: https://hal.inria.fr/hal-03863843.

[30] B. Yang, A. Zine, C. Droz and M. Ichchou. 'Two-dimensional periodic structures modeling based on second strain gradient elasticity for a beam grid'. In: *International Journal of Mechanical Sciences* 222 (2022), pp. 1–13. DOI: 10.1016/j.ijmecsci.2022.107199. URL: https://hal.archives-ouvertes.fr/hal-03622173.

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