RESEARCH CENTRE

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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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2 Overall objectives

2.1 In Summary

The objective of this team is the development of robust and autonomous Structural Health Monitoring (SHM) 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 result 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,

$$\left\{ \begin{array}{rcl} X_{n+1} & = & F X_n + V_n \\ Y_n & = & H X_n + W_n \end{array} \right. \tag{1}$$

where V_n and W_n are zero mean random variables, X_n the process describing the monitored system, Y_n are the observations, F 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)

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

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 multi-inputs multi-output (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 [59].

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:

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

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

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

where $\Delta \stackrel{\Delta}{=} \mathrm{diag}(\Lambda)$, 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:

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

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 $\widehat{\mathscr{H}}_{p+1,q}$ defined by

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

and to define the residual vector

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

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 [53] that the residual is asymptotically Gaussian:

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

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 $\mathscr{J}$ is full rank and Σ is invertible :

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

where

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

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 [52].

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.

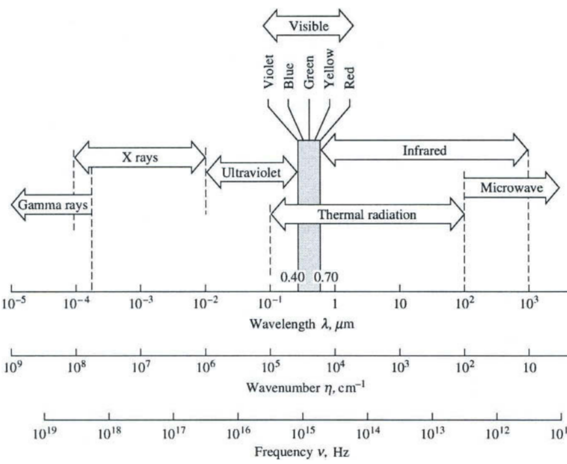

Figure 1: Electromagnetic spectrum - Credit MODEST, M.F. (1993). Radiative Heat Transfer. Academic Press.

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

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

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

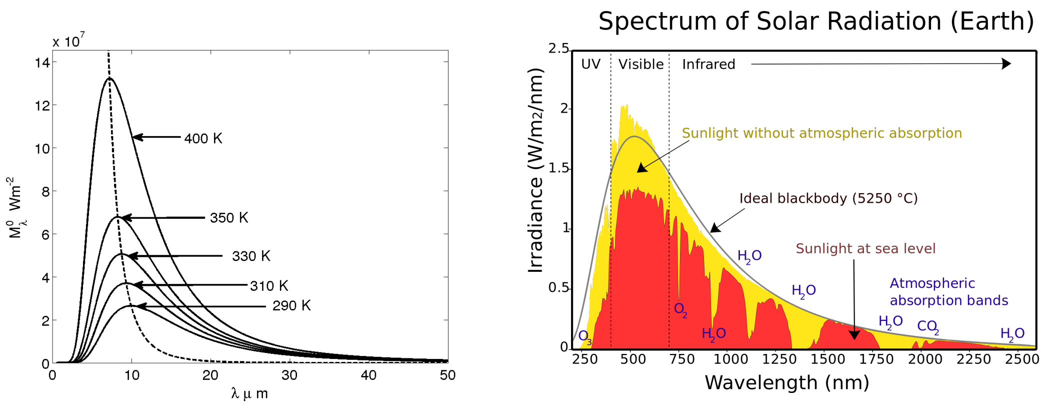

Figure 2: Left: Planck's law at various temperatures - Right: Energy spectrum of the atmosphere

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

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

Let us 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).

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

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

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

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).

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

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.

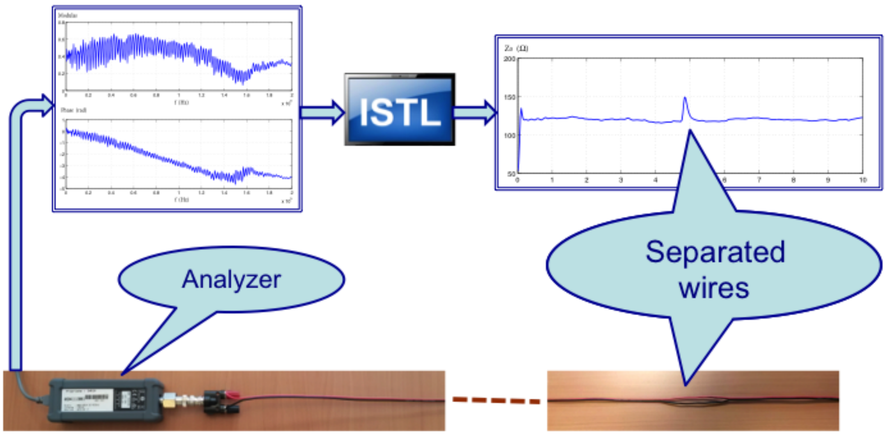

Figure 3: Inverse scattering software (ISTL) for cable soft fault diagnosis

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 reflectometry measurements [11, 14, 58]. 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 [56, 60]. 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 [57]

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

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

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 [55]. The visionary idea of applying this theory to solving the cable inverse problem goes also back to the 1980s [54]. After having completed some theoretic results directly linked to practice [14], [58], 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

$$\nu_1(\omega,x) = \frac{1}{2}\left[Z_0^{-\frac{1}{2}}(x)U(\omega,x) - Z_0^{\frac{1}{2}}(x)I(\omega,x)\right] \tag{35a}$$

$$\nu_2(\omega,x) = \frac{1}{2}\left[Z_0^{-\frac{1}{2}}(x)U(\omega,x) + Z_0^{\frac{1}{2}}(x)I(\omega,x)\right] \tag{35b}$$

with the characteristic impedance

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

These transformations lead to the Zakharov-Shabat equations

$$\frac{d\nu_1(\omega,x)}{dx} + ik\nu_1(\omega,x) = q^*(x)\nu_1(\omega,x) + q^+(x)\nu_2(\omega,x) \tag{37a}$$

$$\frac{d\nu_2(\omega,x)}{dx} - ik\nu_2(\omega,x) = q^-(x)\nu_1(\omega,x) - q^*(x)\nu_2(\omega,x) \tag{37b}$$

with

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

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

In Rennes, the new CityVal automatic metro runs on concrete tracks, where electric heating is used to de-ice the track in cold weather. To optimize the use of the de-icing system and control energy consumption, the manufacturer Siemens relies on thermal modeling research carried out by our team. An article has appeared in the Inria newsletter émergences.

6 Highlights of the year

- Vincent Le Cam was speaker at the COP28 in Dubai, 2 December 2023, at the French Pavillon. He gave a 30min presentation on "Affordable, frugal solutions for sustainable cities and decarbonizing mobility", including a focus on the I4S spinoff ECOTROPY.
- Michael Doehler has defended his HDR on "Robust statistical methods for vibration-based system identification and damage diagnosis" on 07/12/2023 [51].

6.1 Awards

"Prix des doctoriales du département COSYS de l'UGE": Mira Kabbara has received one of three prizes for 2nd year PhD students, and Clément Rigal has received the only prize for 3rd year PhD students. The department counts more than 100 PhD students.

7 New results

7.1 System identification

7.1.1 Efficient Subspace-Based Operational Modal Analysis Using Video-Based Vibration Measurements

Participants: Zhilei Luo, Boualem Merainani, Michael Doehler, Vincent Baltazart, Qinghua Zhang.

Computer vision-based vibration measurement methods are contactless and offer advantages over traditional sensor measurements like accelerometers that have to be installed on the investigated structure. In particular, measurements with a high spatial resolution are obtained at relatively low cost. When processing such measurements for modal analysis with system identification methods, the high dimensional data corresponding to thousands of traditional sensors pose a challenge regarding the computational complexity and the memory requirements of the identification algorithm. In this paper, strategies for dimension reduction in subspace-based modal analysis are implemented and evaluated with regards to the obtained modal parameter uncertainties. In particular, the high spatial resolution of the mode shapes is preserved, while computation time and memory requirements are drastically reduced. The proposed method is applied to numerical and experimental data of a beam. The results have been published in [36, 37].

7.1.2 Model Order Selection for Uncertainty Quantification in Subspace-Based OMA

Participants: Michael Doehler.

Although several uncertainty quantification algorithms have gained widespread use in applications, recent work suggests that the resultant uncertainty estimates are inaccurate when the model order of the dynamic system is misspecified. In practice, the choice of the model order is either based on heuristics, or it relies on procedures assessing the fit of the identified model to data, disregarding the statistical information content in the obtained estimates. In this paper we go back to the roots of the uncertainty propagation in subspace methods and revise it to account for the erroneously chosen model order. The performance of the proposed approach is illustrated on real data collected from a full-scale wind turbine blade. The results have been published in [33].

7.1.3 Sensor placement optimal for the precision of modal parameter estimation with subspace methods

Participants: Michael Doehler.

In this paper we focus on sensor placement for output-only modal analysis, where the objective is to choose those sensor locations yielding a minimal variance in the identification of modal parameters from measurement data. It is heuristically shown that the variance of modal parameters estimated with data-driven subspace identification can be approximated solely based on the process and the measurement noise properties with the Kalman filter and the underlying system model, and is independent of data which are not available at the experimental design stage. The performance of the proposed approach is illustrated on an extensive Monte Carlo simulation for an illustrative example of a mechanical chain system.The results have been published in [34].

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

7.2.1 Localizability of damage with statistical tests and sensitivity-based parameter clusters

Participants: Michael Doehler, Laurent Mevel.

Damage localization based on ambient vibration data in combination with finite element models can be challenging, in particular due to the large number of parameters in the model and noisy measurement data. Changes in different structural parameters can cause similar changes in datadriven features, and vice versa, it can be challenging to identify which parameter caused the deviation in the data. The problem is ill-conditioned and slight variations in the features, due to inherent statistical uncertainty, can lead to significant errors in the result interpretation. A possible solution is sensitivity-based statistical tests in combination with a parameter clustering approach that considers the uncertainties of data-driven features. In this context, this paper introduces the concept of damage localizability, and provides a framework to evaluate it based on the minimum detectable parameter changes, possible false alarms in unchanged parameters, as well as the achievable damage localization resolution. Since clustering approaches depend on user-defined hyperparameters, such as the number of clusters, the second objective of this paper is to optimize the performance of the damage localization, by adjusting the hyperparameters for clustering. A particular strength of the approach is that the analysis can be conducted based on data and a numerical model from the undamaged structure alone, making it a suitable approach to assess and to optimize the diagnosis performance before damage occurs. For proof of concept, a laboratory case study on a simply-supported steel beam is presented, where the localizability of mass changes is analyzed and optimized. The results have been published in [21].

7.2.2 Design and study of an instrumentation and software for permanent monitoring of a cable-stayed bridge

Participants: Thibaud Toullier, Arthur Bouché, Jean Dumoulin.

Permanent monitoring of the structural behavior of civil infrastructures require robust and reliable data acquisition systems. In this study, we present the dynamic monitoring of the Éric Tarbarly bridge in Nantes, France and its related acquisition system. This system enables to follow the temporal evolution of the modal parameters of the structure by storing accelerometers data, external environmental data and the associated metadata thanks to the HDF5 file format. The results have been published in [41].

7.2.3 Vibration monitoring for damage localization: application to a model of the Saint Nazaire bridge

Participants: Ambroise Cadoret, Michael Doehler, Laurent Mevel.

To evaluate the SDDLV damage localization method, a benchmark using sensor data only was proposed. Laboratory tests were carried out on a 1/200-scale model of the central span of the Saint-Nazaire bridge, equipped with accelerometers. The damage introduced simulated the failure of a pair of cables supporting the bridge. The SDDLV method was used to identify changes in the model's flexibility matrix using data measured by accelerometers subjected to white noise. In a second step, a finite element model of the structure was used as part of a static analysis to map damaged elements, without the need for updating. On the model, a particular instance of damage was correctly located in a context where, on the one hand, the frequency shift between the healthy and damaged states is only of the order of 1 percent for the vibration modes useful for analysis and, on the other hand, the correspondence between the modes calculated by finite elements and the modes identified during testing is only approximate.. The results have been published in [29].

7.2.4 Modal-Based Anisotropy Early Warning in Wind Turbine Rotor

Participants: Ambroise Cadoret, Enora Denimal, Laurent Mevel.

Subspace-based fault detection methods are widely used for linear time-invariant systems. For linear time-periodic systems, those methods cannot be theoretically used, due to the intrinsic assumptions associated with those methods in the context of linear time-invariant models. Based on the approximation of time-periodic systems as time-invariant ones, those methods can still be applied and adapted to perform change detection for time-periodic systems, through a Gaussian residual built upon the identified modal parameters and their estimated variances. The proposed method is tested and validated on a small numerical model of a rotating wind turbine, with detection and isolation of a blade stiffness reduction leading to rotor anisotropy. The results have been published in [28].

7.3 Analysis and monitoring of non-stationary systems

7.3.1 Bayesian monitoring of substructures under unknown interface assumption

Participants: Laurent Mevel.

Structural Health Monitoring (SHM) enables assessing in-service structures' performance by localizing structural anomaly instances immediately after their occurrence. Typical SHM approaches monitor the entire structural spatial domain aggravating the required density and cost of instrumentation. Further, with modelbased approaches, the entire structural domain is needed to be defined with high dimensional, computeintensive models rendering the SHM approaches ill-posed and slow especially when the instrumentation is limited and system observability is compromised. Moreover, in absence of high-fidelity models, oversimplification and subsequent model inaccuracies may lead to inaccurate estimation and possibly false alarms even if a subdomain is modeled inaccurately, e.g. support boundaries. To mitigate such issues, stand-alone monitoring focusing only on a subdomain of interest may be a computationally cheaper and prompt approach while being substantially robust to false alarms. Typically, such stand-alone substructure monitoring approaches demand extensive measurement of the interface, which can be a challenge in real-life applications. This paper presents a novel filtering-based online time domain approach for estimating substructure parameters without the need to measure or estimate the substructure interfaces. The proposed component-wise estimation is stand-alone so that the health estimation of the complete structural domain can be undertaken in parallel and later coupled through post-processing. The requirement of the interface measurement has been alleviated by employing an output injection approach. The proposal has been validated on a numerical beam structure subjected to arbitrary forces and subsequently, the sensitivity against noise and damage severity of the proposal has been investigated. Finally, the proposal is validated on a real beam to illustrate its real-life applicability and significance. The work has been published in [18].

7.3.2 Subdomain Fault Isolation for Linear Parameter Varying Systems through Coupled Marginalized Particle and Kitanidis Filters

Participants: Laurent Mevel.

Typically, for linear parameter varying systems, which can potentially get influenced by spatio-temporal external parameters, possible changes in their eigenstructure are not easy to be attributed conclusively to system faults or spatio-temporal parametric variations. Such spatio-temporal variations can although be estimated alongside, yet at the cost of making the estimable system dimension disproportionately large. Such augmented system dimension can thereby jeopardize tracking of the system evolution, either due to computational constraints or due to insufficient measurement channels (ill-posedness). This paper proposes a localized estimation approach wherein only a subdomain of the entire system is considered which reduces the dimension of the estimated model within manageable limits. To focus on the subdomain properties without knowledge of the rest of the model parameterization, a robust algorithm is developed through output injection using a Kitanidis filtering approach to induce robustness in the system parameter estimation against the boundary measurements. Finally, the subdomain model is estimated employing a marginalized filtering approach wherein a particle filter is employed for estimating both the eigenstructure and the controlling parameter while an ensemble Kalman filter estimates the states. The approach is demonstrated with the help of a mechanical system under spatial variation in temperature for which subdomain isolation necessitates the interface to be measured. In the context of numerical application, the induced fault is due to damage and the mechanical model is controlled and parameterized by the internal temperature, whose variations can be significant due to substantial external thermal variations inducing significant variations in dynamic properties. The results have been published in [26].

7.3.3 Boundedness of the Optimal State Estimator Rejecting Unknown Inputs

Participants: Qinghua Zhang.

The Kitanidis filter is a natural extension of the Kalman filter to systems subject to arbitrary unknown inputs or disturbances. Though the optimality of the Kitanidis filter was founded for general time varying systems more than 30 years ago, its boundedness and stability analysis is still limited to time invariant systems, up to the authors' knowledge. In the framework of general time varying systems, this paper establishes upper and lower bounds of the error covariance of the Kitanidis filter, as well as upper bounds of all the auxiliary variables involved in the filter. By preventing data overflow, upper bounds are crucial for all recursive algorithms in real time applications. The upper and lower bounds of the error covariance will also serve as the basis of the Kitanidis filter stability analysis, like in the case of time varying system Kalman filter. The results have been published in [25].

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

7.4.1 Identification of partial differential equations in structural mechanics theory through k-space analysis and design

Participants: Christophe Droz.

This paper presents a method to identify wave equations' parameters using wave dispersion characteristics (k-space) on two-dimensional domains. The proposed approach uses the minimization of the difference of an analytic formulation of the dispersion relation to wavenumbers calculated from solution fields. The implementation of partial differential equations (PDE) resolution on finite element software is explained and tested with analytic solutions in order to generate the test solution fields for the identification process. The coefficient identification is tested on solution fields generated by finite element solver for some 2 ndand 4 th-order equations. In particular the test cases are the equations at different frequencies of deflection of isotropic and orthotropic membrane, flexion of isotropic and orthotropic plate and an original model of orthotropic plate equivalent to a bi-directional ribbed plate. In the limits of the spatial sampling rate and the domain size, the process allows an accurate retrieval of the wave equation parameters. The results have been published in [15].

7.4.2 An Algebraic Wavenumber Identification (AWI) technique under stochastic conditions

Participants: Christophe Droz.

This paper presents an inverse Algebraic Wavenumber Identification (AWI) technique for multi-modal 1D-periodic structures, which can extract complex wavenumbers from steady-state vibration measurements under stochastic conditions. These wave dispersion characteristics provide valuable vibroacoustic indicators for model updating, damage monitoring in operational conditions, or metamaterial design. Wavenumber extraction techniques are highly sensitive to noisy measurements, nonuniform sampling points, or geometrical uncertainties. The proposed formulation relies on algebraic parameters identification to enable the extraction of complex wavenumbers in four scenarios: (a) low Signal Noise Ratio; (b) small perturbation caused by uncertainties on sampling points' coordinates; (c) unknown structural periodicity; (d) nonuniform sampling. This AWI is compared with Inhomogeneous Wave Correlation (IWC) method and INverse COnvolution MEthod (INCOME) to assess the robustness and accuracy of the method. The results have been published in [19].

7.4.3 A Review of Machine Learning Methods Applied to Structural Dynamics and Vibroacoustic

Participants: Christophe Droz.

The use of Machine Learning (ML) has rapidly spread across several fields of applied sciences, having encountered many applications in Structural Dynamics and Vibroacoustic (SD&V). An advantage of ML algorithms compared to traditional techniques is that physical phenomena can be modeled using only sampled data from either measurements or simulations. This is particularly important in SD&V when the model of the studied phenomenon is either unknown or computationally expensive to simulate. This paper presents a survey on the application of ML algorithms in three classical problems of SD&V: structural health monitoring, active control of noise and vibration, and vibroacoustic product design. In structural health monitoring, ML is employed to extract damage-sensitive features from sampled data and to detect, localize, assess, and forecast failures in the structure. In active control of noise and vibration, ML techniques are used in the identification of state-space models of the controlled system, dimensionality reduction of existing models, and design of controllers. In vibroacoustic product design, ML algorithms can create surrogates that are faster to evaluate than physics-based models. The methodologies considered in this work are analyzed in terms of their strength and limitations for each of the three considered SD&V problems. Moreover, the paper considers the role of digital twins and physics-guided ML to overcome current challenges and lay the foundations for future research in the field. The results have been published in [24].

7.4.4 High-resolution models for ultra-fast dynamic analysis of structures with periodic geometry

Participants: Christophe Droz.

The development of "hybrid" fault detection methods, i.e. combining physical simulation models and data-based learning models, offers new prospects in terms of non-destructive evaluation and vibration monitoring (SHM). The use of virtual data (i.e. derived from physical simulations) is often hampered by the increasing complexity of structures and materials, which require substantial computational resources to generate accurate, often multiscale, data in sufficient quantity. This work focuses on a wave formalism that enables intensive simulations of wave-defect interactions in periodic structures subjected to dynamic loads and modeled with a high level of resolution. The results have been published in [44].

7.4.5 Multi-mode propagation and diffusion analysis using the three-dimensional second strain gradient elasticity

Participants: Christophe Droz.

The multi-mode propagation and diffusion properties are crucial informations when studying complex waveguides. In this paper, firstly, the three-dimensional modeling of micro-sized structures is introduced by using the second strain gradient theory. The constitutive relation is deduced while the six quintic Hermite polynomial shape functions are employed for the displacement field. The weak formulations including element stiffness and mass matrices and the force vector are calculated through the Hamilton's principle and the global dynamic stiffness matrix of a unit cell is assembled. Then, free wave propagation characteristics are analyzed by solving eigenvalue problems within the direct wave finite element method framework. The dispersion relations of positive going waves considering the size effects are illustrated. Furthermore, the effects of higher order parameters on the dispersion curves are discussed and the forced responses with two boundary conditions are expounded. Eventually, the wave diffusion including reflection and transmission coefficients are illustrated through simple and complex coupling conditions, respectively. The dynamic analysis of coupled waveguides through the wave finite element method equipped with the second strain gradient is a novel work. The results show that the proposed approach is of significant potential for investigating the wave propagation and diffusion characteristics of micro-sized structures. The results have been published in [23].

7.4.6 Study on thermal storage effectiveness of a novel PCM concrete applied in buildings located at four cities

Participants: Jean Dumoulin.

The implementation of phase change thermal storage technology represents a high-potential strategy for mitigating energy consumption and reducing heating and cooling loads in buildings. However, the practical thermal storage effectiveness is affected significantly by the outdoor thermal conditions specific to each location. This work studied the thermal behaviors of a novel composite concrete containing phase change material (PCM concrete) when inserted into building envelopes. Numerical simulations have been conducted to assess the full-year impact of this PCM concrete on buildings with multi-layer walls, considering four cities with different climates. Results indicate that this novel PCM concrete demonstrates maximum effectiveness in Paris, effectively reducing indoor temperature fluctuations in summer. Conversely, in the other three cities with high solar-air temperatures in summer, the PCM concrete remains melting, reducing its thermal storage effectiveness. Instead, it performs better thermal behaviors during spring and autumn. In summary, the new PCM concrete demonstrates a good capacity to regulate indoor temperature, however, this effectiveness is primarily impacted by the outdoor solar-air temperature. Therefore, to maximize the latent heat storage potential of PCM, it is crucial to select an appropriate PCM with optimal phase change temperature zones, particularly when this technology is implemented in diverse climatic zones. The results have been published in [20].

7.4.7 Use of phase change materials for frost protection applications

Participants: Jean Dumoulin.

This research addresses challenges faced by the transportation and infrastructure sectors during winter, focusing on mitigating ice formation and freezing. The first study investigates the potential of RT5HC paraffin with a melting temperature of 5°C as a phase change material (PCM). Employing various thermal analysis techniques, the study characterizes its thermophysical properties, emphasizing thermal stability and latent heat. Results demonstrate that RT5HC paraffin exhibits good thermal stability, making it suitable for the intended application. Its high latent heat provides an advantage for thermal energy storage, contributing to advancements in PCM applications. The results have been published in [32]. The second study explores the suitability of three kerosenes with melting temperatures of 28, 31, and 35°C for combating urban heat islands. Characterization through ThermoGravimetric Analysis and Differential Thermal Analysis, along with measuring conductivity and thermal diffusivity, reveals that kerosenes possess good thermal stability and can store substantial thermal energy across a wide temperature range. Notably, kerosenes exhibit intermediate rotational phases between liquid and solid phases, leading to the splitting of crystallization peaks during cooling. The results have been published in [45].

7.4.8 Efficient parametric study of a stochastic airfoil system based on hybrid surrogate modeling with advanced automatic kriging construction

Participants: Enora Denimal.

Flutter is one of the most important aeroelastic instability phenomena that arises from the interaction between the structural dynamics of the mechanical airfoil system and the surrounding airflow. This instability phenomenon can lead not only to a reduction in aircraft performance but also to catastrophic structural failure. Therefore, one of the major challenges is to perform parametric and sensitivity studies on the stability behavior of a wing system subject to many random uncertainties in order to achieve a thorough understanding and reliable estimation of the role played by each parameter in the flutter phenomenon. To carry out such a study, an advanced surrogate modeling technique based on kriging and polynomial chaos expansion (PCE) is proposed for the prediction of flutter instability. In addition, a methodology based on hybrid surrogate modeling with advanced automatic kriging construction is discussed to promote an efficient parametric study of the airfoil system with uncertainties subjected to flutter. The Sobol indices highlight that the role played by each random parameter depends strongly on the flow speed and airfoil geometry with complex behaviors, giving valuable insights into the physics and the complexity of flutter. The results have been published in [17].

7.4.9 Multiscale uncertainty quantification of complex nonlinear dynamic structures

Participants: Enora Denimal.

This work aims to investigate the interest in multi-scale uncertainty quantification for nonlinear dynamic systems with friction interfaces. Indeed, such structures experience uncertainties at different time and space scales due to the friction interface. The focus of this work is to quantify and link the uncertainties from friction interfaces at different scales to the nonlinear dynamic response of the structure. A multi-scale kriging approach is employed to propagate the uncertainty. An industrial test rig for dovetail joints will be used as a test case to demonstrate the proposed methodology. The results have been published in [31]. The second study addresses the challenges posed by nonlinearities and uncertainties arising from friction interfaces in large structural assemblies. Conventionally, macroscopic modeling of the contact surface, coupled with a friction law, is employed. However, the friction law, dependent on a few parameters with significant variability, leads to uncertain predictions of dynamic responses. While many efforts have focused on uncertainty quantification in friction interfaces using macro-scale modeling, recent findings emphasize the inadequacy of macroscale models in capturing the physics at the friction interface. Consequently, a multi-scale modeling approach is necessary to efficiently propagate friction contact uncertainties from mesoscale to macroscale, enhancing predictions of the complete nonlinear dynamic response. This work explores the value of multi-scale uncertainty quantification for nonlinear dynamic systems with friction interfaces, specifically examining uncertainties at different scales linked to the dynamic response. The study employs a fan blade root test rig setup as a test case, focusing on friction interfaces between blades and discs. The nonlinear dynamic response is characterized by computing nonlinear normal modes (NNMs). Accurate mesoscale considerations yield pressure and gap distributions at contact interfaces, and uncertainties in mesoscale parameters are propagated to obtain random contact gap and pressure distributions, along with NNMs, across different scales. Multiscale Polynomial Chaos Expansion (PCE) is employed for this propagation and compared to kriging. The results demonstrate that this approach offers profound insights into system understanding at a reduced numerical cost compared to Monte Carlo simulations. The results have been published in [30].

7.4.10 Enhancement of Vehicle Eco-Driving Applicability through Road Infrastructure Design and Exploitation

Participants: Romain Noël.

Energy moderation of the road transportation sector is required to limit climate change and to preserve resources. This work is focused on the moderation of vehicle consumption by optimizing the speed policy along an itinerary while taking into account vehicle dynamics, driver visibility and the road's longitudinal profile. First, a criterion is proposed in order to detect speed policies that are impeding drivers' eco-driving ability. Then, an energy evaluation is carried out and an optimization is proposed. A numerical application is performed on a speed limiting point with 20 usage cases and 5 longitudinal slope values. In the hypothesis of a longitudinal slope of zero, energy savings of 27.7 liter per day could be realized by a speed sign displacement of only 153.6 m. Potential energy savings can increase to up to 308.4 L per day for a -4 percent slope case, or up to 70.5 L per day for an ordinary -2 percent slope, with a sign displacement of only 391.5 m. This results in a total of 771,975 L of fuel savings over a 30 year infrastructure life cycle period. Therefore a methodology has been developed to help road managers optimize their speed policies with the aim of moderating vehicle consumption. The results have been published in [16].

7.4.11 Extracting heat energy through the road pavement: a novel solution with porous concrete

Participants: Domenico Vizzari, Jean Dumoulin.

The sun is by far the largest source of clean energy and the road network is daily exposed to this big amount of radiation. At present, the solar radiation can be directly converted into electrical power thanks to the photovoltaic effect, or harvested by means of a heat-transfer fluid. This paper deals with the second solution, proposing a multilayer road system able to exploit the thermal gradient of the pavement. The system is composed of a porous core, sandwiched between two layers. The base layer is waterproof and it contributes to the mechanical performance of the entire system; the core is a porous concrete mixture for the circulation of the heat-transfer fluid and it works as a solar collector and the top layer is a semi-transparent material designed to support the traffic vehicles, guarantee the skid resistance and maximize the harvested energy. At first, the authors worked on the mix-design of the porous core and of the semi-transparent layer. Secondly, they built a working prototype in order to evaluate harvested heat energy in labcondition. In comparison to the state-of-art, the results show a clear improvement in terms of energy harvesting, leading the way for the construction of a full-scale prototype and a comprehensive evaluation in-situ conditions. The results have been published in [43].

7.4.12 Parametric optimization of fold bifurcation points

Participants: Adrien Mélot, Enora Denimal.

The aim of this work is to optimize the parameters of a mechanical system in order to force fold bifurcation points to appear at targeted frequencies. To this end, an original harmonic balance-based optimization procedure is developed. Functions similar to those employed during bifurcation tracking analyses are used to characterize fold bifurcations in the objective function. The proposed approach is illustrated on a Duffing oscillator with cubic nonlinearity. The results have been published in [38].

7.5 Exploiting new sensor technologies for structural analysis and monitoring

7.5.1 Damage Localization on Composite Structures Based on the Delay-and-Sum Algorithm Using Simulation and Experimental Methods

Participants: Cedric Nzouatchoua, Vincent Le Cam.

Damage detection and localization based on ultrasonic guided waves revealed to be promising for structural health monitoring and nondestructive testing. However, the use of a piezoelectric sensor's network to locate and image damaged areas in composite structures requires a number of precautions including the consideration of anisotropy and baseline signals. The lack of information related to these two parameters drastically deteriorates the imaging performance of numerous signal processing methods. To avoid such deterioration, the present contribution proposes different methods to build baseline signals in different types of composites. Baseline signals are first constructed from a numerical simulation model using the previously determined elasticity tensor of the structure. Since the latter tensor is not always easy to obtain especially in the case of anisotropic materials, a second PZT network is used in order to obtain signals related to Lamb waves propagating in different directions. Waveforms are then translated according to a simplified theoretical propagation model of Lamb waves in homogeneous structures. The application of the different methods on transversely isotropic, unidirectional and quasi-transversely isotropic composites allows to have satisfactory images that well represent the damaged areas with the help of the delay-and-sum algorithm. The results have been published in [22].

7.5.2 New generation of generic synchronized wireless sensors for SHM

Participants: Arthur Bouché, Vincent Le Cam.

PEGASE, the wireless sensor platform developed by University Gustave Eiffel since 2008, is designed for embedded applications. It employs a generic approach in both hardware and software. Hardware versatility is achieved through plug-in motherboards and daughterboards, offering functions for data logging, wireless communication, and robustness for outdoor use. The first generation, launched in 2008, integrated common data logger features and specific wireless capabilities. In 2016, a second version addressed computing power issues, and in 2018, a third version incorporated absolute time-stamping. The fourth-generation PEGASE, introduced in 2023, boasts enhanced electronics with a real-time core, advanced Wi-Fi, and increased storage. Software improvements enable in-phase acquisitions, enhancing synchronization to less than a hundred nanoseconds between two PEGASE cards. The new design, including a daughter board, finds applications in guided waves and acoustic emission. Moreover, efforts are underway to make the board support package and embedded software open source, allowing third parties to leverage PEGASE for their instrumentation cases. This paper presents the novel functionalities of the fourth generation and explores future prospects. The results have been published in [27].

7.5.3 An original smart data sampling for wireless sensor. Application to bridge cable monitoring

Participants: Vincent Le Cam, Arthur Bouche.

Structural health monitoring (SHM) systems often ask for a robust, flexible and costeffective solution. In that domain, since years, the technological development of Wireless Sensor Network try to be an answer. Between many other questions, one of the keypoint in wireless sensing resides in the time synchronization (e.g. how to ensure the same time base between electronic systems that doesn't know each other?). At Gustave Eiffel University, robust and deterministic solutions based on GNSS modules have already been demonstrated [1], the goal of the work presented in this paper is to go deeper into turn-key solutions by implementing and coupling this GNSS-synchronization principle into a low-power FPGA to an Analog-To-Digital converter. This hardware and software association represents a generic solution for signal sampling in a wireless manner. This work is illustrated and demonstrated by an application on the acoustic monitoring of wire-breaks in bridges cables. The results have been published in [35].

7.5.4 Moving train wheel axles automated detection, counting, and tracking by combining AI with Kalman filter applied to thermal infrared image sequences

Participants: Boualem Merainani, Thibaud Toullier, Jean Dumoulin.

Hot boxes, which refer to overheated railroad car wheels and bearings, pose a significant threat to railway operations. Failure to detect and address hot boxes promptly can lead to catastrophic accidents such as derailments and fires. Current wayside hot box detectors operate on the principle that an axle bearing will emit a large amount of heat when it is close to failing. They require principally an infrared (IR) sensor mounted at specific locations along the track, and a signal source coming from a wayside detectors or track circuits to detect if a train is approaching. The IR sensors scanning location, however, should be carefully selected to avoid under/over predicting the operating temperature of the axle bearings and wheels. The dependency of a signal source to activate the system may be problematic as well, not to mention its implementation and maintenance costs. The main contribution of this paper lies with the development of an automatic hot box detection, tracking and counting method by only using the IR cameras. The method combines the YOLO algorithm with the Kalman filter as a tracker. The method was tested with original datasets built with IR images taken from two wayside camera models, cooled and uncooled cameras. The experiments have been conducted on both freight and passenger trains at different times of the day, under clear weather conditions. Apart from the promising results obtained by YOLO, it is found that the Kalman filter further improves the tracking and thus the detection performance, minimizing thereby the incorrect detection or missed detection. The results have been published in [39].

7.5.5 Comparison of Local Weather Sensors Use versus Online Data for Outdoor Monitoring Correction

Participants: Thibaud Toullier, Jean Dumoulin.

The latest improvements in infrared detectors enable the use of infrared thermography in many applications for outdoor temperature measurements through a low cost and easy to maintain solution. However, converting the radiative fluxes received by the infrared camera to the object of interests' apparent surface temperature is a challenging task. It requires us to consider the global radiative heat balance at the sensor level. Such a correction implies taking into account the background contributions (sky, sun, other elements on the scene), the involved transmissions (camera optics, atmosphere, participating media of the scene), etc. As a consequence, supplementary data are needed to achieve quantitative outdoor thermal monitoring. In this study, we propose a comparison of gathering those data from different observation scales: a local weather station, existing sensor networks such as Meteorological Aerodrome

Report (METAR) and open source online satellite data from the European Copernicus program. Finally, the feasibility, advantages and limitations of the proposed methods are discussed. The results have been published in [42].

7.5.6 Distributed strain measurement optical fiber for monitoring of composite patch for offshore steel repair

Participants: Xavier Chapeleau.

The number of floating production, storage and offloading units (FPSO) around the globe is in continuous increase and a relatively high number of them are now almost 20 years aged. The general geographical layout, being in tropical area makes the corrosion a fundamental ageing problem of the steel structures in structural area, like decks or side shell but also inner structure. Therefore, there is a strong need for proposing repair solutions having low impact on their exploitation. Such repair solutions ("cold repair" in contrast with "hot works"), like adhesively bonded FRP (Fiber Reinforced Polymer) requires additional development, in particular in the preliminary characterization and design step, and regarding the durability issues. Use of composite to build onsite repair seems adequate to solve this issue as they require limited heat (80°C) and can easily be installed on various shape, position and surfaces. However, the lack of application cases and design method lead to limited references on the best way to install composite patch repair. This work presents the design methodology, the surface preparation protocol study and the manufacturing protocol of a composite patch developed during the Joint Industrial Project Strength Bond Offshore. The results of the static and fatigue test campaign in tension and bending are also presented. The assessment of the overall capacities of the composite patch repair are compared to a simpler bonded steel repair. The use of distributed strain measurement optical fiber as the new patch monitoring technique applied to composite patch are developed and highlighted [40, 47, 48].

7.5.7 Fiber optic sensors for pavement instrumentation

Participants: Xavier Chapeleau.

On-site pavement instrumentation represents a way to better monitor the behavior of pavement structures in real time, prevent their damage and improve their management. This requires developing instrumentation methods with characteristics adapted to roadway structures: good precision, compatibility with the heterogeneity and rigidity of roadway materials, small footprint, resistance during construction and the service phase. Fiber optic sensors, characterized by their small dimensions, their insensitivity to electromagnetic interference and corrosion and their ability to measure both deformations and temperatures, constitute a promising solution to meet these new needs. This project presents the first results of measurements carried out using continuous fiber optic sensors, in bituminous road structures, tested on the fatigue arena of the Gustave Eiffel University. The technology used (based on Rayleigh backscattering) makes it possible to measure deformations continuously, over a fiber length of 10 m, with a resolution of around 10-6 m/m, at several levels in the roadway. This makes it possible to characterize the longitudinal or transverse deformation fields under the passage of rolling loads much more precisely than traditional sensors, such as strain gauges, which only allow point measurements. [46]

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, Mathias Malandain.

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€.

SDEL-CC Vinci: Lightning localization

Participants: Vincent Le Cam.

After the two previous direct collaborations between the company SDEL-CC and I4S, a third contract is currently running. This new collaboration includes two objectives: industrial transfer for better performance in the "lightning localization" system, and to add new algorithms enabling the product of detecting other defects than lightnings like short-circuit and disphasing. This collaboration is based on an "Action 4" of ANR France Relance, where an SDEL-CC engineer works 4 days per week at the I4S laboratories for the industrial transfer. Total amount: Engineer 2 years at 80% 10/2021–09/2023, plus 30 k€ for equipments.

CETIM: ultrasonic wave monitoring

Participants: Vincent Le Cam, Arthur Bouché.

Two expertise and training sessions were held on the GERONIMO solution developed jointly by CEA and UGE (also called Ondula for railways monitoring or Ondulys for concrete monitoring), with the purpose of application to emit / receive appropriate ultrasonic waves for detection and localization of defects by Acoustic Emission in pipe structures.

CEA List ONDULA2 / Alstom

Participants: Vincent Le Cam.

With CEA-LIST and Alstom-Rail, this project (until 2024) 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.

Sercel: Vibration monitoring

Participants: Michael Doehler, Laurent Mevel.

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).

In 2023, a new transfer for modal analysis with measurements from multiple sensor setups with fixed and moving sensors has been accomplished. Amount for I4S: 3.5k€.

Besides the transfer, an ANR France Relance project with Sercel is ongoing 2022–2024. 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.

Hottinger Brüel & Kjær (HBK): uncertainty quantification for frequency-domain modal analysis

Participants: Michael Doehler, Mikkel Steffensen.

In the context of the PhD of Mikkel Steffensen (DTU Denmark / HBK), a research collaboration with HBK has started on developping methods for uncertainty quantification for input/output frequency-domain modal analysis. Mikkel has spent four months at Inria for joint work on the subject.

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 (2022–2024) 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 nonlinear vibrations. She is a visiting researcher in the Dynamics group, has co-supervied and is currently co-supervising Msc students:

- MSc: Adam Hu, Imperial College London, Powder-based damping of aero-engine blades, E. Denimal and L. Renson, 09/2022-09/2023.
- MSc: Diana Stancic, Imperial College London, Modelling of powder damping in 3D-printed components, E. Denimal Goy and L. Renson, 09/2023-09/2024.

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 has directing the thesis of Neha Aswal (defense 10/2023) with S. Sen at IIT Mandi. The subject is the structural health monitoring of tensegrity structures. Neha has joint the I4S team as a postdoc with the BIENVENUE program (12/2023-11/2025). L. Mevel is co-directing a new thesis of PhD candidate Nikhil Mahar at IIT Mandi since 09/2023.

Collaboration with Université de Sherbrooke

Participants: Christophe Droz, Qinghua Zhang.

C. Droz and Q. Zhang are directing the thesis of Alvaro Gavilan-Rojas with O. Robin at Université de Sherbrooke. The subject is the propagation of guided waves in periodic structures.

9.2 International research visitors

9.2.1 Visits of international scientists

Other international visits to the team

Mikkel Steffensen

Status: PhD student

Institution of origin: Hottinger Brüel & Kjær

Country: Denmark

Dates: 03/02–30/06/2023

Context of the visit: uncertainty quantification of frequency domain modal analysis with M. Doehler

Mobility program/type of mobility: research stay (Danish Innovation Fund)

Alexander Mendler

Status: postdoc

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

Country: Germany

Dates: 04/01–13/01/2023

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: postdoc

Institution of origin: Aarhus University

Country: Denmark

Dates: 05/12–13/12/2023

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

Mobility program/type of mobility: research stay

Subhamoy Sen

Status: professor

Institution of origin: IIT Mandi

Country: India

Dates: 03-04/2023

Context of the visit: preparation of Associated Team proposal, research collaboration with L. Mevel

Mobility program/type of mobility: research stay

9.2.2 Visits to international teams

Research stays abroad

Enora Denimal Goy

Visited institution: Imperial College London

Country: UK

Dates: 11-13/01/2023

Context of the visit: launching of A. Mélot's postdoc and discussion for associate team proposal

Mobility program/type of mobility:

Adrien Mélot

Visited institution: Imperial College London

Country: UK

Dates: 11-13/01/2023, 21/11-15/12/2023

Context of the visit: launching of A. Mélot's postdoc, visit to access a numerical model for an industrial application of the project results

Mobility program/type of mobility:

Enora Denimal Goy

Visited institution: University of Strathclyde

Country: UK

Dates: 6-9/06/2023

Context of the visit: organisation of a workshop related to the RSE award and scientific discussions about the project

Mobility program/type of mobility: RSE workshop award

Alvaro Gavilán-Rojas

Visited institution: Université de Sherbrooke

Country: Canada

Dates: 11/2023 - 10/2024

Context of the visit: Validation of numerical methods using experimental acoustic test facilities at the GAUS group.

Mobility program/type of mobility: Joint PhD degree, co-funded by Université de Sherbrooke and a mobility program awarded by the Matisse doctoral school.

Michael Doehler

Visited institution: ETH Zürich

Country: Switzerland

Dates: 27/02–10/03/2023 and 01/05–05/05/2023

Context of the visit: uncertainty quantification in virtual sensing and filtering

Mobility program/type of mobility: research stay (invitation by ETH)

9.3 European initiatives

9.3.1 Horizon Europe

BRIGHTER BRIGHTER project on cordis.europa.eu

Title: Breakthrough in micro-bolometer imaging

Duration: From December 1, 2022 to November 30, 2025

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- MER MEC FRANCE (INNOTECH), France
- XENICS NV (XENICS), Belgium
- SENSIA SOLUTIONS SL (SENSIA), Spain
- MACQ SA (MACQ), Belgium
- COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES (CEA), France
- CHAUVIN ARNOUX, France
- BIGTRI BILISIM ANONIM SIRKETI, Türkiye
- ARCELIK A.S. (ARCELIK), Türkiye
- LYNRED (LYNRED), France
- UNIVERSITE GUSTAVE EIFFEL, France
- CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS (CNRS), France
- THIMONNIER SAS, France
- DOCAPESCA - PORTOS E LOTAS SA, Portugal
- MARMARA UNIVERSITY (MarUn), Türkiye
- INOV INSTITUTO DE ENGENHARIA DE SISTEMAS E COMPUTADORES INOVACAO (INOV), Portugal

Inria contact: Laurent Mevel

Coordinator:

Summary: Micro-bolometer sensors are compact, light, low power, reliable and affordable infrared imaging components. They are ahead of the cooled infrared sensors for these criteria but lag behind them in terms of performance:

- Existing micro-bolometer technologies have thermal time constants around 10 msec. This is more than 10 times that of cooled detectors.

- Moreover, there is no multispectral micro-bolometer sensor available today for applications such as absolute thermography and optical gas imaging.

BRIGHTER will develop 2 new classes of micro-bolometer solutions to reduce the performance gap with their cooled counterparts:

- Fast thermal micro-bolometer imaging solutions with time constant in the 2.5 to 5 msec range, that is to say 2 to 4 times faster than that of today's micro-bolometer technologies. Read out integrated circuits able to operate up to 500 frames per seconds will also be investigated.

- Multi-spectral micro-bolometer solutions with at least access at the pixel level to 2 different wavelengths in the range 7 to 12 µm.

The developments will focus on pixel technology, Read Out Integrated Circuit, low power edge image signal processing electronic, optics, and image treatment algorithms. All stakeholders of the value chain are involved: academics, RTO, micro-bolometer manufacturer, algorithm developers, camera integrators and end users. They will collaborate to define the best trade-offs for all use-cases.

The 2 new classes of products that will spring from BRIGHTER will generate concrete benefits. They will make it possible to save on material and energy in the manufacturing sector, perform efficient and affordable monitoring of infrastructures and trains, contribute to autonomous vehicles sensor suite, decrease the road casualties among Vulnerable Road Users, better control gas emission in cities and industrial areas. These new usages served by the European industry will allow Europe to increase its market share in the infrared imaging industry.

9.3.2 H2020 projects

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.

9.3.3 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, and a new PhD project has started with PhD candidate N. Delette.

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 ended in 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 – 09/2023
- 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.

  Note: Since 1st October 2023 Thibaud Toullier is part of the permanent staff of the team

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.

CEA

Participants: Romain Noel.

- Partners: CEA/DM2S/STMF.
- Abstract: Within the Inria/CEA collaborative framework I4S and the LMSF started to work together on CFD methods. This collaboration led to a first M2 internship, and we are hoping to continue this collaboration through a PhD project on the use of thermo-chemical potential in LBM.

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

Member of organizing committees

- Xavier Chapeleau
  - Member of the local organizing committee for the conference Diagnobéton, Nantes, 24-27 October 2023

Conference organization

- Vincent Le Cam
  - Organization of SHM@COFREND day at conference "COFREND days", Marseille, 8 June 2023
  - Organization of COSYS doctoral seminar, Marne-La-Vallée, 11 October 2023
- Jean Dumoulin
  - co-chair of session GI5.4 | Ground Penetrating Radar and other geophysical techniques: Applications and Advancements at EGU GA 2023
  - chair of a session at QIRT ASIA 2023
  - chair of a session at 1st LATAM SHM in 2023
- Michael Doehler
  - organizer of special session "Uncertainties in system identification and damage diagnosis" at EVACES 2023, Milan, Italy
- Christophe Droz
  - co-organizer and chair of mini-symposium "Computational methods for modelling complex media" for the invite-only conference "Modelling Complexity in Mechanics", Sep. 2023 Alghero, Italy.
- Enora Denimal Goy
  - Organisation of the "Workshop on Multiscale Structural Dynamics of Uncertain Frictional Interfaces", June 2023, Glasgow, UK
  - chair of the "Uncertainty Quantification" session, UNCECOMP, June 2023, Athens, Greece.
  - is a board member of the GDR EX-MODELI (2023-2024) and organised the yearly workshop of the GDR EX-MODELI as well as the online seminars.

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@COFREND day* is organized grouping around 100 leaders in France in SHM techniques

Member of 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 and GI Division sub-Program Committee member since 2020
  - member of the scientific committee of QIRT (quantitative Infrared Thermography) since 2014
- Qinghua Zhang
  - member of the IFAC Symposium on Fault Detection, Supervision and Safety for Technical Processes (SAFEPROCESS) 2024 scientific committee
  - member of the IFAC Symposium on System Identification (SYSID) 2024 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
- 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

Reviewer

- Michael Doehler was reviewer for IFAC WC 2023.
- Jean Dumoulin was reviewer for QIRT 2023, EGU 2023.
- Qinghua Zhang was reviewer for SAFEPROCESS 2024, SYSID 2024.
- Enora Denimal was reviewer for Nodycon 2023 and OICE 2023.

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.
- Christophe Droz is member of the editorial board of Applied Acoustics section in Frontiers in Acoustics.

Reviewer - reviewing activities

- Christophe Droz was reviewer for the Royal Society Open Science Journal, the Journal of the Acoustical Society of America, Mechanical Systems and Signal Processing, Acoustics, Front. Acoust. and Applied Science and Archive of Applied Mechanics
- 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
- Jean Dumoulin was reviewer for Building and Environment, SPIE Optical Engineering, GI Journal (EGU), QIRT Journal.
- Enora Denimal Goy was reviewer for Mechanical Systems and Signal Processing, Wind Energy Science, Shock and Vibrations, Journal of the Brazilian Society of Mechanical Sciences and Engineering, Applies Sciences.
- Romain Noël was reviewer for Aerospace, Applied Sciences, International Journal of Environmental Research and Public Health, Numerical Algorithms, Physics of Fluids.
- Xavier Chapeleau was reviewer for the journals Sensors, Measurement, Micromachines, Photonics.
- Qinghua Zhang was reviewer for IEEE Transactions on Automatic Control, Automatica.

10.1.4 Invited talks

- Christophe Droz
  - "Resolution schemes within the Floquet Bloch modelling framework", at the International Conference Modelling Complexity in Mechanics, Alghero, Italy, 09/2023.
  - "Periodic structure theory" at IRMAR, Rennes 03/2023.
- Enora Denimal Goy
  - "Structural optimisation of bifurcation diagrams" at the 2023 CornerStone Rolls-Royce Conference, Nottingham University (UK), 26/04/2023.
  - "Meta-modelling for uncertainty quantification and optimisation in nonlinear structural dynamics", Strathclyde University (UK), 07/06/2023."
- Vincent Le Cam
  - wireless and synchronized structural health solutions, ONERA, 22/11/2023
  - introduction keynote on SHM development in France at the 6th SHM@COFREND day in Marseille, 07/06/2023

10.1.5 Leadership within the scientific community

- Enora Denimal Goy is a board member of the GDR EX-MODELI (Exploitation et Modélisation des Dynamiques Non Linéaires).

10.1.6 Scientific expertise

- Christophe Droz was scientific expert for the NCN Poland.

10.1.7 Research administration

- Laurent Mevel
  - deputy head of science of Inria 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.
- Vincent Le Cam
  - Master 2 Civil engineering, Structural Monitoring, 4h, Université de Nantes, France
  - Licence 3 Professional SEICOM, 3h of theoretical lessons and 20H of practical lessons on Embedded and Smart Systems, Université de Nantes, France
  - 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, 4h CM + 32h TP (electronique embarquée, Linux et drivers)
  - Ecole d'Ingénieur Builders, 10h CM, Caen
- 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).

- Christophe Droz
  - MSc 1, Université de Rennes, Siences pour la matière (12h)
  - BSc 2, Mechanical Engineering, Cycle préparatoire intégré INSA Rennes, (29h)

10.2.2 Supervision

PhD students

- Ambroise Cadoret, *Analyse modale opérationnelle pour le suivi de santé structurelle des éoliennes*, L. Mevel, E. Denimal and J.-M. Leroy, Ecole doctorale Matisse, defense 10/2023 [50]
- Barbara Zaparoli Cunha, *Lightweight transmission design through multi-objective optimisations and digital twins*, C. Droz, M. Ichchou, M. Zine, Ecole doctorale MEGA, defense 12/2023
- Neha Aswal, *structural health monitoring for tensegrity structures*, L. Mevel and S. Sen, IIT Mandi, defense 10/2023
- 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, M. Doehler and V. Baltazart, Ecole doctorale Matisse, 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 Matisse, since 10/2022
- Nina Delette, *Development of data-driven approaches for physics-informed wind-turbine digital twins and application to real-world data*, L. Mevel, E. Denimal and J.-L. Pfister, Ecole doctorale Matisse, since 11/2023
- Nikhil Mahar, *machine learning techniques for SHM*, L. Mevel and S. Sen, IIT Mandi, since 09/2023

Postdocs and research engineers

- Vincent Mahé, postdoc Inria, supervised by C. Droz, 09/2023-08/2024
- Boualem Merainani, postdoc funded by SNCF then european Project KDT JU BRIGHTER, supervised by J. Dumoulin, 09/2021-12/2024
- Thibaud Toullier, postdoc funded by Siemens, then ANR France Relance with ECOTROPY, supervised by J. Dumoulin, 09/2022-09/2023
- 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, 02/2022-02/2024
- Neha Aswal, postdoc funded by BIENVENÜE, supervised by Q. Zhang and L. Mevel, 12/2023-11/2025.
- O A Shereena, postdoc at IIT Mandi, co-supervised by L. Mevel, since 09/2023.

Internships

- M1: Ruining Cheng, Lattice Boltzmann simulations of capillary rise using volume of fluid technic, supervised by R. Noel, 05/2023 - 08/2023
- M2: Hoel Keraudren, Lattice Boltzmann simulations of mutli-phase flows with LBM-Saclay, supervised by R. Noel (& A. Cartalade CEA), 03/2023 - 09/2023
- MSc 2: Souleyman Nbosando, Exploring wave phenomena in ropeway transport cable transportation, supervised by C. Droz, 04/2023 - 09/2023
- MSc2: Ali Akbar Rida, Bayesian model updating for robust fault detection, supervised by E. Denimal Goy and L. Mevel, 05/2023-09/2023
- BSc 3: Fatima-zohra Hassam, Geometry analysis in 2D objects, supervised by C. Droz, 05/2023 - 07/2023
- BSc 3: Manon Nolot, Neural Network for friction instability prediction, supervised by E. Denimal Goy and A. Mélot, 05/2023 - 07/2023

10.2.3 Juries

- Enora Denimal Goy
  - PhD Defense - Examinator - Arts et Métiers de Lille. Marielle Debeurre, “Nonlinear dynamics of highly flexible slender beams : efficient numerical strategies in the frequency domain”. Defense December 7, 2023.
  - COS for lecturer (Maitre de conférence) position at LaMCoS, INSA Lyon. May 2023.
- Christophe Droz
  - PhD Defense Examinator - Ecole Centrale de Lyon. Barbara Zaparoli Cunha, "Enhancing Structural Dynamics and Vibroacoustics Design through Digital Twins Enabled by Machine Learning and Transfer Learning". Defense Dec. 2023
- Qinghua Zhang
  - PhD Defense Examinator - Université de Rennes. Ambroise Cadoret, "Analyse modale opérationnelle pour le suivi de santé structurelle des éoliennes". Defense September 22 2023.
- Vincent Le Cam
  - CSI member of PhD candidate Walid Askri "Générateurs flexibles hybrides piézo/tribo électrique pour l’auto-alimentation de capteurs communicants", Université de Nantes / IETR UMR 6164, 11/2021-10/2024.
- Michael Doehler

  - Commission recrutement Enseignant-chercheur mécanique-SHM, Ecole de l'air et de l'espace, 06/2023

- Jean Dumoulin
  - jury member and coordination of the concourse for the recruitment of 2 research engineer at Univ. Eiffel, 06-07/2023

10.3 Popularization

10.3.1 Internal or external Inria responsibilities

- Christophe Droz is co-organizator of the Sci-Rennes seminar series at the Inria center of the University of Rennes (since Sep. 2022).
- Enora Denimal Goy is a member of the national parity commission of Inria.

10.3.2 Articles and contents

- Jean Dumoulin has led an industrial project with Siemens to optimize the use of the de-icing system and control energy consumption of the new CityVal automatic metro in Rennes, using thermal modeling research carried out by our team. An article has appeared in the Inria newsletter émergences.
- Enora Denimal Goy leads the Action Exploratoire No-Bif on the optimisation of nonlinear structures. An article has appeared in the Inria newsletter émergences

10.3.3 Education

- Vincent Le Cam organized several visits of students (collège 3ème, lycéens) at the COSYS-SII/I4S lab at UGE to raise awareness for careers in research.

10.3.4 Interventions

- Vincent Le Cam was speaker at the COP28 in Dubai, 2 December 2023, at the French Pavillon. He gave a 30min presentation on "Affordable, frugal solutions for sustainable cities and decarbonizing mobility", including a focus on the I4S spinoff ECOTROPY.
- Enora Denimal Goy co-organised the workshop "Égalité et sciences : la place des femmes" - 9 mars 2023, Rennes.

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).

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