RESEARCH CENTRE

Inria Centre at Rennes University

IN PARTNERSHIP WITH:

Université Gustave Eiffel

2024
ACTIVITY REPORT

Project-Team

I4S

Inference for Intelligent Instrumented InfraStructures

IN COLLABORATION WITH: Département Composants et systèmes

DOMAIN

Applied Mathematics, Computation and Simulation

THEME

Optimization and control of dynamic systems

Contents

Project-Team I4S 1

1 Team members, visitors, external collaborators 2

2 Overall objectives 3
2.1 In Summary . . . 3
2.2 Objectives . . . 4
2.3 Introduction to physics driven dynamical models in the context of civil engineering elastic structures . . . 4
2.4 Multi-fold thermal effects . . . 5
2.5 Toward a multidisciplinary approach . . . 5
2.6 Models for monitoring under environmental changes - scientific background . . . 6

3 Research program 8
3.1 Vibration analysis . . . 8
3.2 Identification . . . 8
3.3 Detection . . . 9
3.4 Diagnostics . . . 11
3.5 Infrared thermography and heat transfer . . . 11
3.5.1 Infrared radiation . . . 11
3.5.2 Infrared Thermography . . . 13
3.6 Heat transfer theory . . . 13
3.7 Inverse model for parameter estimation . . . 14
3.8 Reflectometry-based methods for electrical engineering and for civil engineering . . . 15
3.8.1 Mathematical model of electric cables and networks . . . 15
3.8.2 The inverse scattering theory applied to cables . . . 16

4 Application domains 17

5 Highlights of the year 17
5.1 Awards . . . 17

6 New results 18
6.1 Sensor technologies and data harvesting . . . 18
6.1.1 Vibration extraction from video image flows . . . 18
6.1.2 Bias and bottlenecks study in outdoor long term thermal monitoring by infrared thermography: Leveraging opportunistic data for temperature estimation . . . 18
6.1.3 Hot box detection on moving targets using way side thermal infrared camera . . . 18
6.1.4 Laboratory and full-scale experiment of a novel hybrid system to harvest energy through concrete pavement . . . 19
6.1.5 Strain transfer model for steel-reinforced optical fiber cable . . . 19
6.1.6 Fiber optic sensors for strain estimation in pavements . . . 19
6.1.7 Investigations on the ageing of GFRP rebar-concrete bond . . . 20
6.1.8 Development and Validation of a Creep Frame . . . 20
6.1.9 Static and Fatigue Strength Assessment of Composite Patch Repair . . . 20
6.2 Complex physical models for structural analysis and design . . . 21
6.2.1 Generalized Dithering using the Lattice Boltzmann Method . . . 21
6.2.2 Pore-scale study of phase change materials . . . 21
6.2.3 A computationally efficient k(ω)-spectral form for partial dispersion analyses within the wave finite element framework . . . 21
6.2.4 Computing the dynamic response of a periodic structure coupled with a nonlinear junction . . . 22
6.2.5 CoSApp: a Python library to create, simulate and design complex systems . . . 22

6.2.6 Control of isolated response curves through optimization of codimension-1 singularities . . . 22
6.2.7 Multi-parametric optimization for controlling bifurcation structures . . . 23
6.2.8 Robust gear design with respect to the primary resonance induced by backlash nonlinearity . . . 23
6.3 Advanced data analysis for complex systems . . . 23
6.3.1 Subspace-based modal identification and uncertainty quantification from video image flows . . . 23
6.3.2 Data-Driven Identification of Noise Covariances in Kalman Filtering for Virtual Sensing Applications . . . 24
6.3.3 Uncertainty-Based Clustering and Tracking of Modal Parameters . . . 24
6.3.4 Modal mass estimation . . . 24
6.3.5 Linear time periodic system approximation based on Floquet and Fourier transformations for operational modal analysis and damage detection of wind turbine . . . 25
6.3.6 Seismic assessment of bridges through structural health monitoring: a state-of-the-art review . . . 25
6.3.7 Electric Cable Insulator Damage Monitoring by Lasso Regression . . . 25
6.3.8 Interval Estimation for Time-Varying Descriptor Systems . . . 26
6.3.9 Time-Delay Estimation for Roadway Survey by Ground Penetrating Radar . . . 26
6.4 Joint data/model analysis . . . 27
6.4.1 State reconstruction for stochastic nonlinear systems with unknown local nonlinearities via output injection . . . 27
6.4.2 Rejection of parametric model errors in a recursive Kalman filter for virtual sensing applications . . . 27
6.4.3 Mitigating ill-posedness in parameter estimation under sparse measurement for linear time-varying systems employing virtual sensor responses . . . 27
6.4.4 Fault Diagnosability Analysis of Multi-Mode Systems . . . 28
6.4.5 Fast dynamic analysis of damaged 1D periodic waveguides . . . 28
6.4.6 Use of bifurcation curves for system identification . . . 28
6.5 Predictive analysis . . . 28
6.5.1 Predictive probability of detection curves based on data from undamaged structures 28
6.5.2 Predictive Probability of Localization Curves (P-POL) for Structures with Changing Environmental Conditions . . . 29

7 Bilateral contracts and grants with industry **29**
7.1 Bilateral contracts with industry . . . 29

8 Partnerships and cooperations **31**
8.1 International initiatives . . . 31
8.1.1 Inria associate team not involved in an IIL or an international program . . . 31
8.1.2 Participation in other International Programs . . . 31
8.2 International research visitors . . . 32
8.2.1 Visits of international scientists . . . 32
8.2.2 Visits to international teams . . . 32
8.3 European initiatives . . . 33
8.3.1 Horizon Europe . . . 33
8.4 National initiatives . . . 35
8.5 Regional initiatives . . . 39

9 Dissemination **40**
9.1 Promoting scientific activities . . . 40
9.1.1 Scientific events: organisation . . . 40
9.1.2 Scientific events: selection . . . 40
9.1.3 Journal . . . 41
9.1.4 Invited talks . . . 42

9.1.5 Leadership within the scientific community . . . 43
9.1.6 Scientific expertise . . . 43
9.1.7 Research administration . . . 43
9.2 Teaching - Supervision - Juries . . . 43
9.2.1 Teaching . . . 43
9.2.2 Supervision . . . 44
9.2.3 Juries . . . 46
9.3 Popularization . . . 46
9.3.1 Specific official responsibilities in science outreach structures . . . 46
9.3.2 Productions (articles, videos, podcasts, serious games, ...) . . . 46
9.3.3 Others science outreach relevant activities . . . 47

10 Scientific production **47**
10.1 Major publications . . . 47
10.2 Publications of the year . . . 48
10.3 Cited publications . . . 52

Project-Team I4S

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Keywords

Computer sciences and digital sciences

- A6.1.5. – Multiphysics modeling
- A6.2.1. – Numerical analysis of PDE and ODE
- A6.2.4. – Statistical methods
- A6.2.5. – Numerical Linear Algebra
- A6.2.6. – Optimization
- A6.3.1. – Inverse problems
- A6.3.3. – Data processing
- A6.3.4. – Model reduction
- A6.3.5. – Uncertainty Quantification
- A6.4.3. – Observability and Controlability

Other research topics and application domains

- B3.1. – Sustainable development
- B3.2. – Climate and meteorology
- B3.3.1. – Earth and subsoil
- B4.3.2. – Hydro-energy
- B4.3.3. – Wind energy
- B4.3.4. – Solar Energy
- B5.1. – Factory of the future
- B5.2. – Design and manufacturing
- B5.9. – Industrial maintenance
- B6.5. – Information systems
- B7.2.2. – Smart road
- B8.1. – Smart building/home
- B8.1.1. – Energy for smart buildings
- B8.1.2. – Sensor networks for smart buildings
- B8.2. – Connected city

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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 $\mathcal{Y}_+$ and stack the column vectors Y_k^T for $k = 0, -1, \dots, -P$ to get the data matrix $\mathcal{Y}_-$; 3/ the product $\mathcal{H} = \mathcal{Y}_+ \mathcal{Y}_-$ is a Hankel matrix. Then, matrix $\mathcal{H}$ on the one hand, and the observability matrix $\mathcal{O}(H, F)$ of system (2) on the other hand, possess almost identical left kernel spaces, asymptotically for M, N large. This property is the basis of subspace identification methods. Extracting $\mathcal{O}(H, F)$ using some Singular Value Decomposition from $\mathcal{H}$ then (H, F) from $\mathcal{O}(H, F)$ using a Least Square approach has been the foundation of the academic work on subspace methods for many years. The team focused on the numerical efficiency and consistency of those methods and their applicability on solving the problems above.

There are numerous ways to implement those methods. This approach has seen a wide acceptance in the industry and benefits from a large background in the 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 :

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

The (canonical) parameter vector in that case is :

$$\theta \triangleq \begin{pmatrix} \Lambda \\ \mathrm{vec}\Phi \end{pmatrix} \tag{6}$$

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 [72].

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

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

be the output covariance and Hankel matrices, respectively; and: $G \triangleq \mathbf{E}\left(X_k Y_{k-1}^T\right)$. 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:

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

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:

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

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

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

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

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

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

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

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

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

and to define the residual vector

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

Let θ be the actual parameter value for the system which generated the new data sample, and $\mathbf{E}_\theta$ be the expectation when the actual system parameter is θ. From (14), we know that $\zeta_N(\theta_0)$ has zero mean when no change occurs in θ, and nonzero mean if a change occurs. Thus $\zeta_N(\theta_0)$ plays the role of a residual.

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

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

The central limit theorem shows [66] 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 :

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

where

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

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 [65].

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 $\mathscr{J}\,\mathscr{J}_{\Phi\theta}$, where $\mathscr{J}_{\Phi\theta}$ 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 :

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

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

3.5 Infrared thermography and heat transfer

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

3.5.1 Infrared radiation

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

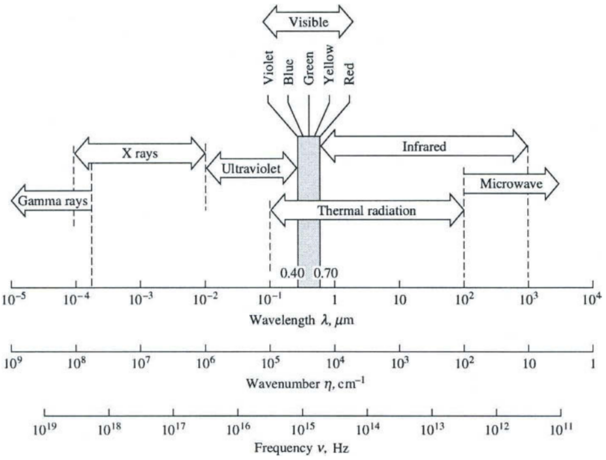

Figure 1: Electromagnetic spectrum - Credit MODEST, M.F. (1993). Radiative Heat Transfer. Academic Press.

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

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

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

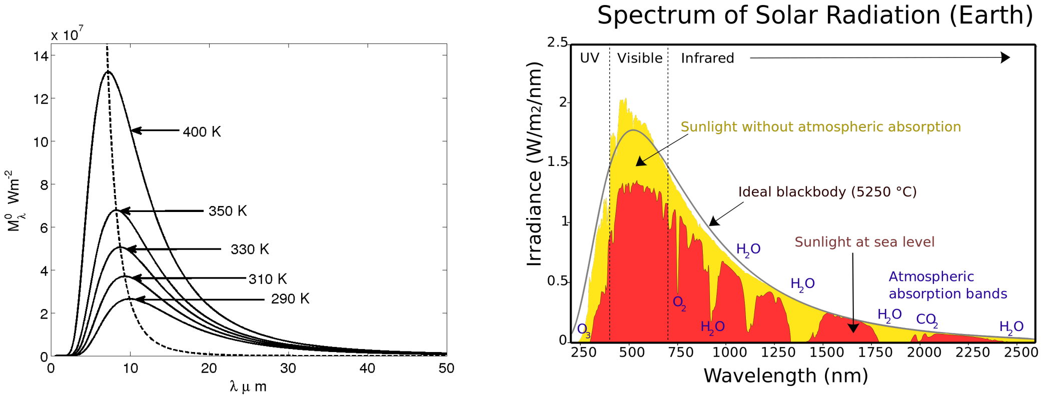

Figure 2: Left: Planck's law at various temperatures - Right: Energy spectrum of the atmosphere

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).

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

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 $\nabla.()$ 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.

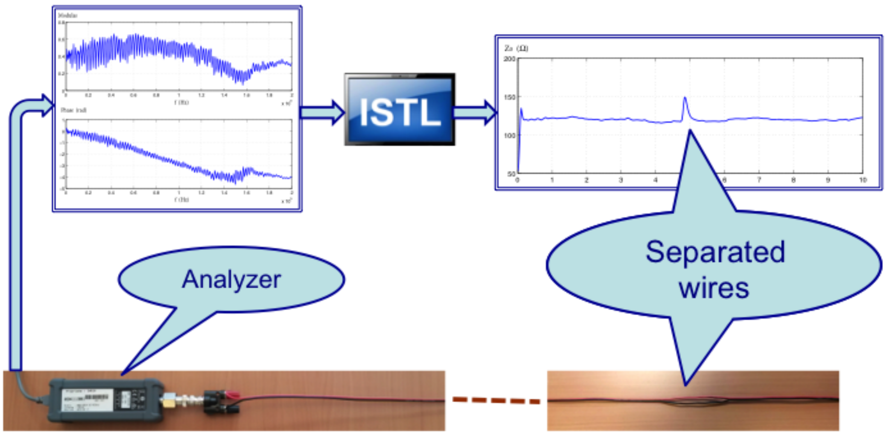

Figure 3: Inverse scattering software (ISTL) for cable soft fault diagnosis

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 [12, 15, 71]. 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 [69, 73]. 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 [70]

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

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

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 [68]. The visionary idea of applying this theory to solving the cable inverse problem goes also back to the 1980s [67]. After having completed some theoretic results directly linked to practice [15], [71], we started to successfully apply the inverse scattering theory to cable soft fault diagnosis, in collaboration with GEEPS-SUPELEC [12].

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

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

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 Highlights of the year

- Creation of the new project-team "Inference for Intelligent Instrumented InfraStructures" (I4S) in 11/2024, successor of the previous project-team "Inférence Statistique pour la Surveillance et la Sécurité des Structures" (I4S).
- Christophe Droz has defended his HDR "A Unified Wave Finite Element Modeling and Identification Framework for Periodic Structures: Towards Metamaterial Twins" on 02/12/2024.

5.1 Awards

- Michael Doehler has received the IOMAC Leadership Award at the 10th International Operational Modal Analysis Conference in Naples, Italy. The award is offered by the permanent IOMAC Committee to individuals for their seminal contributions to the development of operational modal analysis.

6 New results

6.1 Sensor technologies and data harvesting

6.1.1 Vibration extraction from video image flows

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

With adequate image processing methods, motion signals can be extracted from video image flows for vibration analysis. In this way, the pixels in selected regions of interest within the images act as a dense network of contactless sensors distributed over the whole structure. In this work, the efficiency of this video-based approach is demonstrated with laboratory experiments on a cantilever beam, in particular, by evaluating its capability for detecting weak damages mimicked by slight mass modifications. To this end, the steerable filter-based method (ST), that recovers displacements from local phase, is first extended to overcome its motion limitation of one pixel size. Then, the performance of the improved motion extraction method is compared with two other well-established methods. Furthermore, a novel image-based motion estimation method that explicitly considers perturbations due to ambient light changes and disturbance by background features is developed. Results are published in [25, 41].

6.1.2 Bias and bottlenecks study in outdoor long term thermal monitoring by infrared thermography: Leveraging opportunistic data for temperature estimation

Participants: Thibaud Toullier, Jean Dumoulin.

This study aims to assess the impact of the targeted scene and environmental variables on in situ longterm thermal monitoring by infrared thermography. It also addresses projection errors arising from camera perspectives and digitization. Over a span of 3 years, extensive measurements were conducted at two instrumented test sites, yielding a valuable dataset for analysis. This work introduces and discusses the model used to convert the collected data into surface temperature estimations and its associated parameters' sensitivities. Subsequently, it delves into the effects of camera resectioning on infrared measurements. Finally, the study investigates the influence of environmental parameters and proposes a strategy to correct for these effects, with and without additional sensors (opportunistic data) and additional in-situ measurements, published in [28].

6.1.3 Hot box detection on moving targets using way side thermal infrared camera

Participants: Boualem Merainani, Thibaud Toullier, Jean Dumoulin.

In a context of European rail traffic growing rapidly, infrastructure managers are pushed to develop reliable solutions to improve safety and operational performance. In the present study we focus on the bogie component, a complex and important element in rail-road cars. Overheated rail-road car wheels and bearings known as hot boxes, are a major threat for any railway operation. With the advancements in both image sensor technology and processing capabilities, machine vision-based techniques may provide cost-effectiveness and easy solutions for hot wheels and hot axle bearings detection.In this research work, automatic detection, tracking and counting of hot boxes is addressed through the implementation of way side infrared thermal cameras. First a discussion on thermal cameras required performances is proposed and new uncooled fast pixel sensors are introduced. Implementation on a real railway is presented and discussed. A new and affordable thermal vision-based wayside monitoring method is proposed. It combines panoramic thermal images with deep learning (DL)-based object detection algorithm. Panoramas were created, from thermal image sequences collected, by cooled and uncooled cameras, during field experiments on both freight and passenger trains. The results yield promising perspectives, notably in maintaining high safety standards, at a more budget-friendly cost. Publications are [34, 48].

6.1.4 Laboratory and full-scale experiment of a novel hybrid system to harvest energy through concrete pavement

Participants: Domenico Vizarro, Jean Dumoulin.

Havesting energy from the sun through the pavement is a powerful lever to fight against the worldwide energy crisis. Indeed, the pavement surface is daily exposed to the sun light and represents an enormous source of potential harvesting. So far, solutions involving photovoltaic cells placed on the pavement or using a heat-transfert fluid circulating through the structure are studied. Recently, we have developed a novel hybrid system at University Gustave Eiffel combining the two solutions. The structure is made of a porous concrete layer where a heat-transfert fluid is circulating sandwiched between a waterproof structural concrete layer placed below and a photovoltaic layer placed on top. The photovoltaic layer is composed of PV cells protected by a semi-transparent layer designed to support the traffic vehicles, guarantee the skid resistance and enabling the passage of the sun light. At the beginning of the research, the semi-transparent layer and the porous concrete have been optimized in terms of energy harvesting and a laboratory size prototype have been constructed. This work also considers a full scale prototype of the hybrid system tested in real climatic conditions and shows some first results regarding thermal harvested energy measured around 240 W/m2 in the specific conditions tested [36].

6.1.5 Strain transfer model for steel-reinforced optical fiber cable

Participants: Mira Kabbara, Qinghua Zhang, Xavier Chapeleau.

In distributed optical fiber sensors, strain transfer is usually described through a simplified one-dimensional equation, derived from continuum mechanics. This equation, in which a parameter known as the strain-lag parameter takes into account the cable's geometric and mechanical characteristics, establishes a relationship between the measured longitudinal strain profile within the optical fiber and the real strain profile occurring in the host material. In the case of steel-reinforced optical fiber cables, appreciated for their resistance to breakage during on-site instrumentation, a notable discrepancy between the measured and actual strain profiles is revealed especially in the presence of a strain gradient, indicating that the ability to transfer strain from the host material to the optical fiber is restrained using this type of cable. This work assesses numerically the strain transfer model for steel-reinforced optical fiber sensors in the presence of a strain gradient generated by two void inclusions in a concrete beam. Good accuracy of the strain transfer model is observed by the comparison with a 3D finite element simulation. The result points out also the critical necessity of precisely determining the strain-lag parameter [40].

6.1.6 Fiber optic sensors for strain estimation in pavements

Participants: Xavier Chapeleau.

The need to develop more efficient pavement management systems has driven continuous improvement in structural health monitoring (SHM) systems for road infrastructures. Factors such as low energy consumption, minimal disruption (small-sized and lightweight devices), resistance to environmental conditions, high durability, and sensitivity are some of the possible improvements worthy of exploration.

Fiber optics appear to have several of these desired characteristics. This work considers strain measurements performed using fiber optic cables installed at various levels in pavement structures tested on the accelerated pavement testing facility at the Université Gustave Eiffel (or fatigue carousel). The results reveal that strains measured with this technology closely align with those obtained using traditional strain gauges. However, an advantage of fiber optics is that they enable distributed measurements over long distances with high precision (10 m with a measurement interval of 2.6 mm in this study). These measurements highlight a significant variability in pavement strains, seemingly attributable to the heterogeneity of pavement materials and variations in layer thicknesses. Furthermore, the responses of two pavement structures are evaluated. The findings show that the new pavement structure exhibits good bonding and continuous strain distribution, while the rehabilitated pavement structure exhibits partial sliding at the interface and strain discontinuity. For the new pavement structure, the strains are well predicted using a bonded interface, while for the rehabilitated pavement structure, the strains are predicted using a thin elastic interface layer with a low elastic modulus. Results are published in [16, 21].

6.1.7 Investigations on the ageing of GFRP rebar-concrete bond

Participants: Xavier Chapeleau.

Durability investigations are needed to better understand degradation mechanisms and provide optimized safety coefficients. While several researchers have explored the durability of FRP rebars, only few have examined the evolution of the FRP-concrete interfacial bond. The GFRP-to-concrete bond behaviour was experimentally studied, focusing on the combined effects of thermally accelerated ageing in alkaline environment and sustained loading. The evolution of the residual interfacial properties over ageing is presented, allowing for a discussion on the influence of sustained load on the aging process, published in [33].

6.1.8 Development and Validation of a Creep Frame

Participants: Arij Fawaz, Xavier Chapeleau.

In industry, structural bonding can play an important role in repairing and reinforcing metallic structures. One reliable method is to use fracture mechanics tests that allow the determination of fracture toughness in mode I, mode II or mixed-mode. Such strategy can be used during the analysis of the initial design, but also through the aging study. Few studies were conducted to inspect the effect of applied load on the mechanical behavior of bonded joints. An adaptation of the sample's geometry is required to allow the combination of both ELS and creep configurations. This study adapts the sample's geometry to allow the combination of both End Load Split test and creep configurations. The new sample configuration is compared to a traditional sample geometry. An optical fiber is employed to monitor crack propagation, thereby enhancing this comparison. The obtained toughness characterizations allowed us proposing a design strategy that was assessed in regards with experimental tests conducted on large size steel samples reinforced with adhesively bonded composite. This work is published in [35, 57].

6.1.9 Static and Fatigue Strength Assessment of Composite Patch Repair

Participants: Xavier Chapeleau.

Marine and Offshore industries are looking for rapid, efficient and qualified repair solutions for damaged or corroded structures. Patch made of composite materials can offer such qualities. Small-scale and large-scale specimens were tested in static and fatigue, and numerical simulations were done in order to develop a robust methodology for the strength assessment of composite patch repairs. The static resistance of the patch designs and manufacturing processes is determined by tensile and bending tests. The results show that long scarf specimens have a higher resistance and that the manufacturing process has little influence. Finally, fatigue tests on long scarf specimens, and for the two studied manufacturing processes, are detailed and compared with a FPSO (Floating Production Storage Offloading) histogram [50].

6.2 Complex physical models for structural analysis and design

6.2.1 Generalized Dithering using the Lattice Boltzmann Method

Participants: Romain Noel.

A generalized dithering approach using the Lattice Boltzmann Method (LBM) is proposed. This generalization enables to experiment different models, and to adapt them accordingly to targeted features and problems. As illustrations, 4 models are introduced and tested, including anisotropic gradient-based relaxation time and enhanced equilibrium distribution function, aiming for robust quality and artefacts reduction. These models are implemented on Graphics Processing Units (GPU) and generically interfaced with the OBLiX framework. The several test-cases performed demonstrate that such models yield better qualitative and quantitative results, proving the adaptability of the generalization. By providing a general framework for dithering using the Lattice Boltzmann Method, this allows an adaptation of the algorithms to complex situations deviating from classically encountered cases. Published in [26].

6.2.2 Pore-scale study of phase change materials

Participants: Romain Noel, Clement Rigal.

In recent years, there has been growing interest in the development of reversible thermal storage systems for urban development. One of these systems consists of a fluid flow carrying microcapsules containing a phase-change material (mPCM) circulating in a porous layer integrated into the urban structure. To understand the physical mechanisms at work within this fluid and the solid that surrounds it, which is still incomplete to date, we need to study the various scales involved, particularly that of the pore, which is often difficult to measure experimentally and the subject of much numerical work. The present work aims to investigate the effect of the motion of the mPCM on the the melting process occurring in its inside, focuses on the rotational motion and deals with two scales: the capsule scale and the pore scale. In order to determine the order of magnitude of the angular velocity of small particles moving in a porous medium, a pore-scale numerical study is conducted, using a coupling between lattice Boltzmann method and discrete elements method. The resulting velocities are used in an other numerical study conducted at capsule scale in which an enthalpy-based model provides a realistic solution for the phase change. This work is presented in [62, 63].

6.2.3 A computationally efficient k(ω)-spectral form for partial dispersion analyses within the wave finite element framework

Participants: Alvaro Camilo Gavilan Rojas, Qinghua Zhang, Christophe Droz.

This work addresses the computation of frequency-dependent dispersion curves (i.e., k(ω)) and wave modes within the framework of the Wave Finite Element Method (WFEM) and in the context of highdimensional periodic unit cell models. Numerous applications, ranging from phononics to vibroacoustics, now rely on dispersion analyses or wave expansion over a subset of eigensolutions resulting from the resolution of an eigenvalue problem with a T-palindromic quadratic structure (T-PQEP).

To exploit the structure of finite element models, various structure-preserving linearizations have already been developed to achieve partial wave resolution of large T-PQEP, primarily targeting the dominating (least decaying) waves. We derive an alternative linearization of the T-PQEP for the k(ω) problem, which leads to enhanced targeting of the eigenvalues around the unit circle and reduces the inaccuracies induced by root multiplicity. A specific form of the problem is then proposed as an optimal compromise between ease of implementation, numerical stability, convergence and accuracy enhancement. The performance of our proposed linearization is compared against existing ones across various iterative eigensolvers, since the generalized eigenvalue problems involve complex non-hermitian matrices, which are not extensively included in eigensolvers. Results indicate that the proposed linearization should be favored for the WFEM, as it provides numerical enhancements in dispersion and wave vectors computation for large eigenvalue problems, as well as for further wave expansion applications [18, 59].

6.2.4 Computing the dynamic response of a periodic structure coupled with a nonlinear junction

Participants: Vincent Mahe, Adrien Melot, Christophe Droz.

Structures constituted of assembled sub-components are often subject to nonlinear effects due to the presence of joints or contacts, which can induce higher-order harmonics of the source excitation. In the context of periodic structures, these nonlinearities cannot be tackled using the Floquet-Bloch theory in its usual harmonic formulation. This study hence presents an adaptation of the classical Floquet-Bloch theory to address multi-harmonic systems arising from a finite number of localized nonlinearities in periodic waveguides. We adopt the Harmonic Balance Method to recast the governing equations into a nonlinear algebraic system, which can then be solved using numerical continuation algorithms. To demonstrate the validity and benefit of this approach, the predictions derived from the proposed methodology are compared to results obtained through conventional Finite Element analysis. Excellent agreement and a notable reduction in computational cost are observed. This efficient procedure for analysing the nonlinear dynamic response of periodic waveguides opens up new possibilities in the study of damaged composite structures [42].

6.2.5 CoSApp: a Python library to create, simulate and design complex systems

Participants: Mathias Malandain.

CoSApp, for Collaborative System Approach, is an object-oriented Python framework that allows domain experts and system architects to create, assemble, simulate and design complex systems. The API of CoSApp is focused on simplicity and explicit declaration of design problems. Special attention is given to modularity; a very flexible mechanism of solver assembly allows users to construct complex, customized simulation workflows. CoSApp handles steadystate simulation, as well as time-dependent dynamic systems, and multimode systems with event-based mode transitions [20].

6.2.6 Control of isolated response curves through optimization of codimension-1 singularities

Participants: Adrien Melot.

We introduce a computational framework for controlling the location of isolated response curves, i.e. responses that are not connected to the main solution branch and form a closed curve in parameter space. The methodology relies on bifurcation tracking to follow the evolution of fold bifurcations in a codimension-2 parameter space. Singularity theory is used to distinguish points of isola formation and merger from codimension-2 bifurcations and an optimization problem is formulated to delay or advance the onset or merger of isolated response curves or control their position in the state/parameter space. We illustrate the methodology on three examples: a finite element model of a cantilever beam with cubic nonlinearity at its tip, a two-degree-of-freedom oscillator with asymmetry and a two-degree-of-freedom base-excited oscillator exhibiting multiple isolas. Our results show that the location of points of isola formation and mergers can effectively be controlled through structural optimization [22, 61, 45].

6.2.7 Multi-parametric optimization for controlling bifurcation structures

Participants: Adrien Melot.

Bifurcations organize the dynamics of many natural and engineered systems. They induce qualitative and quantitative changes to a system's dynamics, which can have catastrophic consequences if ignored during design. In this paper, we propose a general computational method to control the local bifurcations of dynamical systems by optimizing design parameters. We define an objective functional that enforces the appearance of local bifurcation points at targeted locations or even encourages their disappearance. The methodology is an efficient alternative to bifurcation tracking techniques capable of handling many design parameters ($>10^2$). The method is demonstrated on a Duffing oscillator featuring a hardening cubic nonlinearity and an autonomous van der Pol-Duffing oscillator coupled to a nonlinear tuned vibration absorber. The finite-element model of a clamped-free Euler–Bernoulli beam, coupled with a reduced-order modelling technique, is also used to show the extension to the shape optimization of more complicated structures. Results demonstrate that several local bifurcations of various types can be handled simultaneously by the bifurcation control framework, with both parameter and state target values. [23]

6.2.8 Robust gear design with respect to the primary resonance induced by backlash nonlinearity

Participants: Adrien Melot.

This work investigates the influence of uncertain tooth profile modifications on the nonlinear dynamic response of a spur gear pair induced by a backlash nonlinearity. To this end, an original approach based on bifurcation tracking is developed. The equations of motion are solved in the frequency domain with the harmonic balance method (HBM) coupled to an arc-length continuation algorithm and a bordering technique. The evolution of the bifurcation points with respect to the uncertain parameter is computed deterministically. To characterize the severity of the resonance, we introduce two criteria, namely the amplitude of the response at the resonance peak and the width of the resonance hysteresis. Uncertainty is then introduced by means of probability densities of the tip relief within the tolerance interval. Probability density functions of various indicators of the severity of vibro-impacts can be computed with Monte-Carlo simulation with minimal computational burden. We show that the optimum profile correction differs significantly from the one obtained in the purely deterministic case.[46, 60].

6.3 Advanced data analysis for complex systems

6.3.1 Subspace-based modal identification and uncertainty quantification from video image flows

Participants: Boualem Merainani, Bian Xiong, Zhilei Luo, Vincent Baltazart, Michael Doehler, Jean Dumoulin, Qinghua Zhang.

The performance of different motion extraction methods from video image flows is compared in the context of OMA, where natural frequencies, damping ratios and mode shapes with high spatial resolution are estimated together with their uncertainty bounds using covariance-driven subspace identification. The compared methods are evaluated with the help of reference laser displacement measurements as well as a finite element model of the beam, revealing differences in the accuracy of the estimated mode shapes depending on the chosen method for motion extraction. Aiming to investigate early structural damage detection, experiments are carried out under small structural changes and the results are compared to a reference state with the help of estimated uncertainties. Small but statistically significant changes in the modal parameters are detected, showing the potential of the vision based framework for SHM. Furthermore, the robustness against ambient light changes and disturbance by background features is investigated in the context of OMA. Results are published in [25, 41].

6.3.2 Data-Driven Identification of Noise Covariances in Kalman Filtering for Virtual Sensing Applications

Participants: Michael Doehler.

The optimality of the Kalman filter for state-estimation depends on the knowledge of the process and measurement noise covariance. In applications, these covariances are often treated as tuning parameters, often adjusted in a heuristic manner based on user-defined performance criteria. While several methods to identify them from data exist, some require the use of optimization algorithms, or inversion of large matrices, which is numerically inefficient. In this work we review a simple data-driven subspace identification approach to estimate the process and measurement noise covariance, and apply it in the context of virtual sensing. The estimates of the noise covariances are obtained from the residuals of a regression of the banks of shifted Kalman filter states obtained from data and the model matrices of the monitored system. The performance of the approach is illustrated on a numerical example of a chain system by comparing the system states in unmeasured locations to the Kalman filter-based predictions [37].

6.3.3 Uncertainty-Based Clustering and Tracking of Modal Parameters

Participants: Johann Priou, Michael Doehler.

Automated modal parameter tracking is an essential part of vibration-based structural health monitoring of engineering structures, e.g., bridges, high-rise building, wind turbines, amongst others. In this work, we conceive a robust algorithm for accomplishing this task. First, the modal parameters are extracted with by greedy clustering the stabilization diagram, which is based on covariance-driven subspace identification and the related uncertainty quantification. After the selection of a set of relevant modal parameters to be monitored, the tracking is performed by an active search of stable modes close to the reference ones, again using statistical criteria and automated clustering. The applied strategies allow for a robust method, allowing also for relatively strong variations in the natural frequencies or the MAC without losing track of the monitored modes. Finally, when EOVs (Environmental and Operational Variables) are measured and training and testing periods are defined, a neural network is trained based on the tracked frequencies and the EOVs, with the goal of correcting the environmental influence on the estimated frequencies based on the model predictions. In doing so, a distance metric is defined for damage detection, which is robust to environmental perturbations under the measured EOVs. The whole framework is showcased on monitoring data of several full-scale bridges [51, 52, 53].

6.3.4 Modal mass estimation

Participants: Mikkel Tandrup Steffensen, Michael Doehler.

In operational modal analysis with exogenous inputs, the modal parameters are estimated based on partly measured inputs and outputs. Different algorithms can be used, like combined deterministic stochastic subspace identification (CSI) algorithms or the poly-reference Least Squares Complex Frequency (pLSCF) algorithm. Common for both types of algorithms are the computation of modal mass to normalize the estimated mode shapes according to the inputs. In this work, the modal mass computation for CSI and the pLSCF-algorithm is revisited, where a particular focus is put on the assumption on the intersample behavior that is required for the relation between estimates obtained from the discrete-time system (where the data comes from) and the corresponding continuous-time system (where the modal mass is computed). The discretization methods: zero-order hold, first-order hold, and the impulse invariant discretization are studied and discussed. It is shown that the modal mass estimates are heavily dependent on the discretization approach used. The results are illustrated in the context of Monte Carlo simulation of a six-degrees-of-freedom chain system [58].

6.3.5 Linear time periodic system approximation based on Floquet and Fourier transformations for operational modal analysis and damage detection of wind turbine

Participants: Ambroise Cadoret, Laurent Mevel.

Operational Modal Analysis (OMA) identifies modal properties of mechanical structures from vibration data collected from a few sensors under operation conditions. These methods are widely used to monitor civil engineering structures that are modeled as time-invariant systems. However, when dealing with wind turbines and rotating machines, many dedicated OMA techniques were developed to deal with the time-periodic behavior. Existing methods pre-process the data to adapt them to classical identification techniques. Yet, these methods present limitations as either requiring a high number of measured rotation periods, assuming the assumption of an isotropic rotor (i.e. undamaged), or the knowledge of the rotational speed. This work proposes to lift these difficulties by proving that the application of the classical system identification methods can produce meaningful estimates for anisotropy monitoring. It results in the possibility of using classical identification methods without modification to retrieve the system matrices of the approximated time-invariant system. The identified modes can be used reliably for the monitoring of operating wind turbines and more especially for fault detection, at the expense of losing a part of the complete description of the periodic system. The resulting anisotropy monitoring approach and its capacities are illustrated in two cases [17].

6.3.6 Seismic assessment of bridges through structural health monitoring: a state-of-the-art review

Participants: Michael Doehler.

The present work offers a comprehensive overview of methods related to condition assessment of bridges through Structural Health Monitoring (SHM) procedures, with a particular interest on aspects of seismic assessment. Established techniques pertaining to different levels of the SHM hierarchy, reflecting increasing detail and complexity, are first outlined. A significant portion of this review work is then devoted to the overview of computational intelligence schemes across various aspects of bridge condition assessment, including sensor placement and health tracking [19].

6.3.7 Electric Cable Insulator Damage Monitoring by Lasso Regression

Participants: Qinghua Zhang.

Since the discovery of electricity, electric cables have become ubiquitous in human constructions, from machines to buildings. Insulators play a crucial role in ensuring the proper functioning of these cables, so it is important to monitor their possible damage, which can be caused by environmental contamination, severe temperature variations, and electrical and mechanical stress. While shunt conductance is a direct health indicator of cable insulation, measuring the cable average shunt conductance is not sufficient for the detection of localized insulator damage, since localized conductance variations are diluted over a long cable length in such measurements. The objective of this work is to assess the feasibility of reflectometry techniques for the monitoring of insulator damage in electric cables. To this end, the estimation of localized conductance variations is investigated based on electrical measurements made at one end of a cable. To avoid estimating a large number of discretized conductance values along a long cable, the proposed method relies on sparse regression, which automatically focuses on localized conductance variations at unknown positions caused by accidental insulator damage. Numerical simulations show the potential of this method for fast estimation of localized shunt conductance variations [30].

6.3.8 Interval Estimation for Time-Varying Descriptor Systems

Participants: Qinghua Zhang.

We investigate the state interval estimation problem for discrete-time linear time-varying descriptor systems subject to unknown but bounded system uncertainties. We propose a zonotope-based interval estimation method in an optimization framework. First, we present a novel zonotope-based interval estimator structure, in which the estimated interval bounds of each state component have design parameters independent of those of the other state components. Then the widths of the jointly estimated intervals enclosing every state component are simultaneously minimized by solving parallel L1 optimization problems via linear programming. Finally, a simulation study shows the effectiveness and higher accuracy of the proposed method compared with existing methods. The work is published in [29].

6.3.9 Time-Delay Estimation for Roadway Survey by Ground Penetrating Radar

Participants: Vincent Baltazart.

Time-delay estimation (TDE) using ground penetrating radar (GPR) is of great importance in roadway surveys. We have proposed a general overview of GPR in road engineering over the past 20 years in [64], and describe several existing GPR processing methods and antennas configurations for application to control the flexible pavement structures in layer thickness and interlayer debondings. The most common TDE methods require the signal picking in the time domain, which can be manual or automatic. Advanced TDE processings have been developped in the past to improve the time resolution of GPR and to achieve the control of thin pavement layers. It is now combined with ultra wide-band stepped-frequency radar technique to survey interlayer debonding.

Within this domain, the conventional signal processing methods, namely, FFT-based methods, apply uniform sampling strategy for TDE, which require numerous frequency sampling points, leading to lengthy data acquisition time and large data storage, especially for ultra-wideband (UWB) radar. In [27], the co-prime sampling strategy is developped as an alternative solution to control thin pavement layers by exploiting off-grid sparse Bayesian learning (OGSBL), referred as co-prime-OGSBL. In our scheme, the sampling rate of GPR signals with co-prime sampling strategy is then greatly reduced compared with the uniformsampling, which therefore reduces the data acquisition burden and computational complexity. Both simulation and experimental results demonstrate the efficiency and accuracy of the proposed method in the estimation of time-delays and thickness. Most of these works rely on the existing experimental data base which have been previously collected at UGE 's fatigue carousel and to the ANR Acimp project.

6.4 Joint data/model analysis

6.4.1 State reconstruction for stochastic nonlinear systems with unknown local nonlinearities via output injection

Participants: Neha Aswal, Adrien Melot, Qinghua Zhang, Laurent Mevel.

This work addresses state estimation for dynamical systems involving localized unknown nonlinearities. Direct application of linear state estimation techniques, e.g., the Kalman filter, would yield erroneous state estimates. Existing approaches in the literature either assume or estimate the nonlinearities. Alternatively, the present paper proposes to reject the unknown nonlinearities as if they were unknown disturbances. By applying an existing disturbance rejection technique, the need to know or to estimate the nonlinearities is avoided. The efficiency of the proposed method is demonstrated through numerical simulations on a nonlinear mechanical system [31].

6.4.2 Rejection of parametric model errors in a recursive Kalman filter for virtual sensing applications

Participants: Michael Doehler.

The performance of the Kalman filter is often hindered by the discrepancies between a model used to realize the filter and the true model of the data-generating system. While some methods to account for those errors exists, the majority is restricted to Luenberger's observers. The objective of this work is to develop a Kalman filter where the effect of parametric model errors is rejected from the state and observation equations before the development of the state estimate, and without the explicit knowledge of the error terms. For this purpose, errors in a physical parameter of a parametrized mechanical system are modelled as additive terms in the state and observation equations by means of first-order perturbation analysis. The rejection step is achieved with an injection of a shaped output nullifying the effect of the added terms. A state observer is then derived under the assumption that the injected shaped outputs and the system states are uncorrelated. The performance of the proposed approach is illustrated on experimental data of a plate system [38].

6.4.3 Mitigating ill-posedness in parameter estimation under sparse measurement for linear time-varying systems employing virtual sensor responses

Participants: Qinghua Zhang, Laurent Mevel.

Monitoring linear time-varying (LTV) systems using model-based approaches typically requires dense instrumentation and high- fidelity support models, resulting in significant computational and financial costs. Bayesian filtering-based methods adopt a joint state-parameter estimation approach for LTV system monitoring wherein states/parameters are observed as well as inferred from the measurements. Eventually, sparsity in measurement while dealing with high-fidelity models can aggravate the ill-posedness in the estimation diverging the estimation to impractical or no solutions. To enhance estimation resolution and precision, an alternative approach can be supporting estimation with virtual sensor measurements sampled from future time steps. To leverage virtual measurements, the estimation needs to be time-delayed, enabling the observation of states/parameters through measurements taken at both current and subsequent time steps, thereby alleviating the ill-posedness. This method has been explored for an LTV spring-mass-dashpot system, where the numerical investigation utilizes an interacting filtering environment to estimate states and parameters in the presence of sparse measurements. The study has shown how incorporating additional information can stabilize the estimation process, leading to improved estimates for both states and parameters [55, 56].

6.4.4 Fault Diagnosability Analysis of Multi-Mode Systems

Participants: Mathias Malandain.

Multi-mode systems can operate in different modes, leading to large numbers of different dynamics. Consequently, applying traditional structural diagnostics to such systems is often untractable. To address this challenge, we present a multi-mode diagnostics algorithm that relies on a multi-mode extension of the Dulmage-Mendelsohn decomposition. We introduce two methodologies for modeling faults, either as signals or as Boolean variables, and apply them to a modular switched battery system in order to demonstrate their effectiveness and discuss their respective advantages [39].

6.4.5 Fast dynamic analysis of damaged 1D periodic waveguides

Participants: Alvaro Camilo Gavilan Rojas, Qinghua Zhang, Christophe Droz.

We extend the Bloch wave-based reduced order models in the Wave Finite Element Method (WFEM) framework for fast wave-damage interaction analysis. It aims at fault detection and diagnosis of periodic structures. A finned tube heat exchanger, which can be seen as a 1D system, is used as a numerical application. Reduced model results and performance are compared to a standard WFEM model. Diffusion curves are obtained more than a hundred times faster with the proposed scheme, moving toward massive generation of wave-damage scenarios and indicators to perform damage detection [54].

6.4.6 Use of bifurcation curves for system identification

Participants: Adrien Melot.

We propose a methodology to carry out nonlinear system identification based on bifurcations. The proposed approach relies on fold bifurcation curves identified experimentally through control-based continuation and an optimization framework to minimize the distance between the experimental and numerical curves computed with bifurcation tracking analyses. The approach is demonstrated on a nonlinear model of base-excited energy harvester with magnetic force nonlinearity [43, 44].

6.5 Predictive analysis

6.5.1 Predictive probability of detection curves based on data from undamaged structures

Participants: Michael Doehler.

We develop a model-assisted approach for determining predictive probability of detection curves. The approach is “model-assisted,” as damage-sensitive features are evaluated in combination with a numerical model of the examined structure. It is “predictive” in the sense that probability of detection (POD) curves can be constructed based on measurement records from the undamaged structure, avoiding any destructive tests. The approach can be applied to a wide range of damage-sensitive features in structural health monitoring and non-destructive testing, provided the statistical distribution of the features can be approximated by a normal distribution. In particular, it is suitable for global vibration-based features, such as modal parameters, and evaluates changes in local structural components, for example, changes in material properties, cross-sectional values, prestressing forces, and support conditions. The approach explicitly considers the statistical uncertainties of the features due to measurement noise, unknown excitation, or other noise sources. Moreover, through confidence intervals, it considers model-based uncertainties due to uncertain structural parameters and a possible mismatch between the modeled and the real structure. Experimental studies based on a laboratory beam structure demonstrate that the approach can predict the POD before damage occurs. Ultimately, several ways to utilize predictive POD curves are discussed, for example, for the evaluation of the most suitable measurement equipment, for quality control, for feature selection, or sensor placement optimization [24].

6.5.2 Predictive Probability of Localization Curves (P-POL) for Structures with Changing Environmental Conditions

Participants: Michael Doehler.

In this paper, an approach to assess the detectability of damages is applied to strain and inclination measurements for the first time, demonstrating the universality of the method. Moreover, it is analyzed how changes in the environmental and operational variables (EOVs) affect the predicted POD. The results demonstrate that the predicted POD are valid even in the presence of environmental changes, but they depend on the user-defined hyperparameters of the algorithms that remove the environmental effects from the measurements. Therefore, the hyperparameter selection is critically discussed and an optimal monitoring strategy is outlined [47].

7 Bilateral contracts and grants with industry

7.1 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€.

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.

CETIM: fiber optic monitoring

Participants: Xavier Chapeleau.

CETIM is conducting fatigue testing on a tank until it bursts, using existing fiber optic sensors based on Bragg gratings for deformation measurement points. This expertise project aims to enhance this setup with additional fiber optic sensors for distributed deformation measurements in a testing campaign, with the goal to compare the effectiveness of these two monitoring technologies. Total amount: 20k€

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 three contracts to Sercel, involving technical development and support (2020–2023).

Besides the transfer, an ANR France Relance project with Sercel has been accomplished (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 one month at Inria in 2024 for joint work on the subject.

8 Partnerships and cooperations

8.1 International initiatives

8.1.1 Inria associate team not involved in an IIL or an international program

PhyNET

Title: Integrating eigenspace and physical space information via PINN architecture towards stochastic distance-based damage detection

Duration: 2024 -> pres.

Coordinator: Subhamoy Sen

Partners:

- IIT Mandi (India)

Inria contact: Laurent Mevel

Summary: Structural Health Monitoring (SHM) is an essential process that involves real-time monitoring of the physical condition of a mechanical structure in the presence of environmental variations. This monitoring relies on data collection through sensors and the utilization of reference models that describe the structure in its initial state. This coupling between sensors and numerical models proves to be extremely challenging, primarily due to the significant disparity between the limited number of available sensors and the high complexity and dimensionality of the models required for accurate monitoring. The fondamental objective of this research project is to improve state-of-the-art SHM strategies coupling experimental data with numerical modelling by combining them with physics-informed neural networks (PINNs). The numerical model should assist the PINN in enhancing limited real-world data with model-generated, damage-sensitive physical features. This integration aims at generalizing SHM methods while making them adaptable to various dynamic conditions and improve their robustness to noise, sensor defects, and model errors.

8.1.2 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.

Collaboration with Imperial College London

Participants: Adrien Melot.

A. Melot collaborates with Imperial College London on the topic of structural optimisation for nonlinear vibrations. He is a visiting researcher in the Dynamics group.

Collaboration with IIT Mandi

Participants: Laurent Mevel, Christophe Droz, Adrien Melot.

L. Mevel has been directing the thesis of Neha Aswal (defense 10/2023) with S. Sen at IIT Mandi, who 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.

8.2 International research visitors

8.2.1 Visits of international scientists

Other international visits to the team

Mikkel Tandrup Steffensen

Status: PhD student

Institution of origin: Hottinger Brüel & Kjær / DTU

Country: Denmark

Dates: 30/01–28/02/2024

Context of the visit: uncertainty quantification of frequency domain modal analysis with Michael 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: 15/07–19/07/2024

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

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

8.2.2 Visits to international teams

Research stays abroad

Alvaro Camilo Gavilan 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.

Laurent Mevel, Christophe Droz, Adrien Melot, Alvaro Camilo Gavilan Rojas

Visited institution: IIT Mandi

Country: India

Dates: 22/09–05/10/2024

Context of the visit: collaboration on physics-informed machine learning

Mobility program/type of mobility: Inria Associated Team PhyNET

Michael Doehler

Visited institution: Technical University of Munich (TUM), Chair of Non-Destructive Testing

Country: Germany

Dates: 14/10–18/10/2024

Context of the visit: collaboration on reliability assessment of SHM/NDT methods

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

8.3 European initiatives

8.3.1 Horizon Europe

BRIGHTER

Participants: Laurent Mevel, Jean Dumoulin, Thibaud Toullier, Boualem Merainani, Vincent Baltazart.

BRIGHTER project on cordis.europa.eu

Title: Breakthrough in micro-bolometer imaging

Duration: 2022–2025

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.

USES2

Participants: Vincent Le Cam, Romain Noel.

USES2 project on cordis.europa.eu

Title: USES of novel Ultrasonic and Seismic Embedded Sensors for the non-destructive evaluation and structural health monitoring of critical infrastructure and human-built objects

Duration: 2023–2027

Partners:

- UGE
- Universidad Politécnica de Madrid (UPM)
- COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES (CEA)
- FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV (IZFP)
- BUNDESANSTALT FUER MATERIALFORSCHUNG UND -PRUEFUNG (BAM)
- ISAMGEO ITALIA S.R.L. (Isamgeo)
- UNIVERSITE LIBRE DE BRUXELLES (ULB)
- AIRBUS DEFENCE AND SPACE SA (AIRBUS)
- ZENSOR (Zensor)
- UNIVERSITY OF BRISTOL (UBRI)

Inria contact: Vincent Le Cam

Coordinator: Université Gustave Eiffel, Odile Abraham

Summary: Infrastructure makes up the arteries of modern society, providing people, organisations with all necessities – from utilities to housing and transport. However, its maintainance can be difficult. While non-destructive evaluation is the process currently being used, it is disruptive to infrastructure. An interesting possibility is to use condition-based structural health monitoring (SHM) with sensors. However, these sensors currently provide local information making it inefficient for the size and complexity of infrastructure. The EU-funded USES2 project aims to develop an alternative by bringing together new sensor technologies, improved processing tools and full-mechanical-waveform-based imaging, as well, as training researchers to efficiently utilise these tools. This will allow for efficient larger-scale infrastructure structural health monitoring, essential for their everyday use.

8.4 National initiatives

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 with its final report in 2024.

ANR PRC SWEAT-City

Participants: Romain Noel, Jean Dumoulin.

- Duration: 2024 – 2028
- Budget: 409 k€
- Title: Simulation of Water Evaporation within Artificial ground for Thermo-regulation of the City
- Abstract: The global warming and the more extreme events related implies that cities will be concerned by Urban Heat Island (UHI) effect more often and more intensively. Pavements cover between 30% and 40% of city areas and have a strong effect on the UHI. Studies are showing that two major phenomena can be used and then must be studied to reduce the effect of pavements on UHI: The albedo and the evaporation of water. The increase in albedo has a beneficial effect on the surface temperature of pavements but increases radiation on the vertical surfaces of the city. The present proposal focuses on the effect of water evaporation on UHI. Research on that topic is increasing in the recent years, and only few papers are available on the numerical simulation. However, the evaporation of porous media is a complex phenomenon by its geometry, its interactions between the matrix and fluids, the phase change etc. This complexity leads to macroscopic models with numerous parameters that are hard to obtain experimentally and to optimize. The aim of the project is to develop a heat and mass numerical model that considers evaporation in a construction material. The model is based on a multiscale approach combining the ability of Lattice Bolzman Method at the pore scale and Finite Element at the macro scale. Experiments will be carried out at different scales to validate the modelings. Finally experiments in simulated real life situation within the Sense City facility will be performed and simulated in order to validate the models.

ANR JCJC Archi-Noise

Participants: Christophe Droz.

- Duration: 2024 – 2028
- Budget: 286 k€
- Title: Architected materials with meso-scale interactions for Noise and vibration control
- Abstract: Noise, vibration, and harshness (NVH) impact multiple industries, affecting health, system longevity, and sustainability. Despite advances in NVH mitigation materials, performance gains are plateauing due to constraints like cost, compactness, adaptability, and structural integrity. ArchiNoise seeks to redefine material design by exploring architected meta-structures at meso- and macro-scales, surpassing traditional vibro-acoustic limits. It will adapt nano-scale physics and electromagnetism concepts to structural engineering, creating scattering effects akin to Bragg and locally resonant bandgaps, but independent of periodic unit-cell dimensions or oscillator mass. These novel waveguiding phenomena will target broadband NVH control. ArchiNoise will develop theoretical, computational, and phenomenological tools to design and optimize these materials. By integrating enriched continuum theories, vibroacoustics, inverse wave-based identification, and lattice-based periodic modeling, it will pioneer lightweight NVH solutions.

ANR France 2030 ExcellenceS City-FAB / CD 92

Participants: Jean Dumoulin, Thibaud Toullier, Mathias Malandain.

- Duration: 2024 – 2028
- Partners: CD 92, UGE laboratories
- Budget: 600 k€, 80 k€ for the team
- Title: Analysis of uses, and study of comfort and urban atmosphere on an avenue scale
- Abstract: The objective is to anticipate and adapt road redevelopment projects by aiming at better sharing of mobility spaces, making travel safer and enhancing the environment. These objectives meet the issues of sustainable cities and territories. This project focuses on the environmental effects of developments, in particular concerning thermal comfort, air quality and acoustic comfort. Our contribution to this project focuses on in-situ monitoring and data-driven studies.

ANR SCaNING

Participants: Vincent Le Cam.

- Duration: 2021 – 2025
- 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.

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.

CETIM

Participants: Michael Doehler, Xavier Chapeleau.

- Duration: 09/2024–08/2025
- Partners: CETIM, I4S, UGE/MAST-SMC. Budget: 100 k€
- Abstract: This research collaboration funded by CETIM aims at developing a thesis project focused on data fusion and AI using data from SHM sensors to create predictive models for fatigue damage (initiation and propagation of cracks) in welded structures. This preliminary study focuses on evaluating SHM sensors and the processing and fusion of data related to the considered use case.

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 the collaboration continues through the PhD project of Clément Bardet (2024–2027) on the use of thermo-chemical potential in LBM.

IFPEN

Participants: Laurent Mevel.

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 (2023–2026).

8.5 Regional initiatives

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 Noel.

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).

9 Dissemination

9.1 Promoting scientific activities

9.1.1 Scientific events: organisation

Conference organization

- Vincent Le Cam
  - Organization of SHM@COFREND day, Bordeaux, 20/03/2024
- Jean Dumoulin
  - co-chair of session GI4.4 | Urban Geophysics & UASs Remote Sensing approaches in Geoscience research platforms for the 21st century at EGU GA 2024
  - chair of a session at QIRT 2024
  - chair of a session at WCNDT20
  - chair and co-chair of 2 sessions at SPIE Optics + Photonics 2024
- Michael Doehler
  - chair of a session at IOMAC 2024
  - chair of a session at EWSHM 2024
- Vincent Le Cam
  - member of EWSHM 2024 award committee and chair of two sessions

9.1.2 Scientific events: selection

Chair of conference program committees

- Vincent Le Cam
  - head and general secretary of the EWSHM scientific committee
- Jean Dumoulin
  - vice chairman of QIRT steering committee since 2024

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 IOMAC scientific committee
- Vincent Le Cam
    - member of the IWSHM scientific committee
    - member of SHM@COFREND 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 IOMAC 2024, EWSHM 2024.
- Jean Dumoulin was reviewer for QIRT 2024, EGU 2024.
- Vincent Baltazart was reviewer for EGU 2024.
- Qinghua Zhang was reviewer for SAFEPROCESS 2024, SYSID 2024.
- Vincent Le Cam was reviewer for EWSHM 2024.

9.1.3 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.
- 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 European Journal of Mechanics - A/Solids, Mechanical Systems and Signal Processing, Finite Elements in Analysis and Design, Journal of Sound and Vibration.
- Laurent Mevel was reviewer for Mechanical Systems and Signal Processing
- Michael Doehler was reviewer for Mechanical Systems and Signal Processing, Journal of Sound and Vibration, Engineering Structures
- Jean Dumoulin was reviewer for Building and Environment, SPIE Optical Engineering, GI Journal (EGU), QIRT Journal.
- Romain Noel 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 Journal of Civil Structural Health Monitroing, Engineering Structures, Measurement, Sensors and Actuators A Physical.
- Vincent Baltazart was reviewer for Engineering Structures, Automation in Construction, Measurement, Remote Sensing, IEEE Trans. Geoscience and Remote Sensing.
- Qinghua Zhang was reviewer for IEEE Transactions on Automatic Control, Automatica, Mechanical Systems and Signal Processing.
- Adrien Mélot was reviewer for Mechanical Systems and Signal Processing

9.1.4 Invited talks

- Christophe Droz
  - A Wave Finite Element Framework for model-based guided wave testing, Mandi, India, 25/09/2024.
- Vincent Le Cam
  - introduction keynote on SHM development in France at the 7th SHM@COFREND day in Bordeaux, 20/03/2024
- Michael Doehler
  - “Statistical uncertainties in vibration-based system identification”, keynote lecture at Digital Bridge congress, Munich, Germany, 17/10/2024
- Jean Dumoulin
  - “Ultra Time Domain Infrared Thermography in outdoor monitoring" invited talk at WCNDT20, 20th World Conference on Non-Destructive Testing, May 2024, Incheon, Corée du Sud.
  - “Thermal monitoring of structures and systems by Infrared thermography in outdoor conditions", Short course Lecture, QIRT 2024, July 2024, Zagreb, Croatie
  - “Monitoring of transport infrastructures using ground-based infrared thermography: results, progress, challenges, and perspectives" invited talk at SPIE Optics and Photonics, Conference 13144: Infrared Remote Sensing and Instrumentation XXXII, August 2024, San Diego, USA.

9.1.5 Leadership within the scientific community

- Vincent Le Cam
  - co-chair of SHM@COFREND: this activity branch of the COFREND (French Confederation for Non-destructive Testing) aims at uniting the national SHM community from academia and industry, and to promote and standardize the SHM sector in France.
  - 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
- Michael Doehler
  - co-leader of the working group "GT SHM Data" within SHM@COFREND. The GT focuses on scientific issues, technical challenges and standards of the SHM sector related to handling and processing of structural monitoring data. The GT involves around 50 people from academia and industry in France.

9.1.6 Scientific expertise

- Christophe Droz was scientific expert for NWO Netherlands.

9.1.7 Research administration

- Laurent Mevel
  - deputy head of science of Inria Rennes
  - member of Commisision d'Evaluation at Inria
- Vincent Le Cam
  - deputy co-head of COSYS department at Université Gustave Eiffel
- Jean Dumoulin
  - member of Commisision d'Evaluation des chercheurs du Ministère de la Transition Ecologique (MTE)
- Xavier Chapeleau
  - member of Commisision d'Evaluation des chercheurs du MTE

9.2 Teaching - Supervision - Juries

9.2.1 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 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
  - M1 ITI, fibre-optique, 8h, IUT Nantes
  - "Monitoring and auscultation : Optical fiber sensors", 2h, Infrastar Training School, October 2024
- Romain Noel
  - École des Mines de Saint-Étienne, Master 2, Fluid Mechanics Applications: Plenary conference (2h)
  - École des Mines de Saint-Étienne, Master 1, Advanced Fluid Mecanics: Lectures (6h) + practical lessons (6h)
  - École Centrale de Nantes, Master 2, Data Signal and Image: Lectures (4h) + practical lessons (4h)
- Christophe Droz
  - MSc 1, Modélisation en Action, Dpt. Mathématiques, Université de Rennes (50h)
  - MSc 2, Contrôle non destructif et identification, Dpt. Sciences pour la matière, Université de Rennes (4h)
- Alvaro Camilo Gavilan Rojas
  - Master 2, Mécanique et Matériaux, Contrôle non destructif et identification, 1.5h CM + 7.5h TD, Université de Rennes
- Lucas Rouhi
  - L1 SVE, Maths pour la biologie 1, 15h TD, Université de Rennes

9.2.2 Supervision

Preview not available.

PhD students

- Cédric Nzouatchoua, *Apport des réseaux de capteurs à ultrasons sans-fil dans la surveilllance de l’état de santé des structures composites*, M. Bentahar, Vincent Le Cam and N. Collin, Ecole doctorale SPI, defense 12/2024.
- Zhilei Luo, *Methods for robust and efficient vision-based operational modal analysis*, Michael Doehler, Qinghua Zhang, and Vincent Baltazart, Ecole doctorale Matisse, defense 10/2024.
- Clément Rigal, *Modélisation multi-échelle d’écoulements convectifs avec des matériaux à changement de phase micro-encapsulés à travers un milieu poreux*, Y. Hoarau D. Funfschilling Romain Noel A. Chouippe , Ecole doctorale MSTII, since 12/2021.
- Mira Kabbara, *Modélisation et caractérisation de capteurs à fibre optique continus*, Qinghua Zhang, F. Bourquin, Xavier 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, Xavier Chapeleau, Ecole doctorale SIS, since 10/2022.
- Alvaro-Camilo Gavilan-Rojas, *Reduced order models for non-destructive evaluation of periodic structures*, Christophe Droz and Qinghua 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*, Laurent Mevel, E. Denimal and J.-L. Pfister, Ecole doctorale Matisse, since 11/2023.
- Nikhil Mahar, *machine learning techniques for SHM*, Laurent Mevel and S. Sen, IIT Mandi, since 09/2023.
- Marios Kaminiotis, *Embedded self-powered sensor devices for passive monitoring of composite components*, Vincent Le Cam and Romain Noel and Bastien Chapuis, Ecole docotrale STIC, since 01/2024.
- Zakariae Moutaouakil, *Estimating/Modelling the statistical degradation laws of the secondary road network from video-based pavement monitoring devices*, Laurent Mevel, Ph. Foucher, and Vincent Baltazart, within the scope of the ROAD-AI project with Cerema, since 10/2024.
- Clément Bardet, *Simulation of multiphase flow coupled with temperature using Lattice Boltzmann Method and chemical potential.*, Laurent Mevel and Romain Noel, Ecole doctorale Matisse, since 10/2024.
- Lucas Rouhi, *Non-local architected meta-structures for lightweight vibro-acoustic design*, Christophe Droz, Qinghua Zhang, Ecole Doctorale Matisse, since 09/2024.
- Benoit Senard, *An algebraic framework for phononic systems modelling*, Christophe Droz, Michael Doehler, Ecole Doctorale Matisse, since 10/2024.

Postdocs and research engineers

- Vincent Mahé, postdoc Inria, supervised by Christophe Droz, 09/2023-08/2024.
- Boualem Merainani, postdoc funded by SNCF then european Project KDT JU BRIGHTER, supervised by Jean Dumoulin, 09/2021-12/2024.
- Johann Priou, research engineer ANR France Relance with Sercel, supervised by Michael Doehler, 02/2022-02/2024.
- Neha Aswal, postdoc funded by BIENVENÜE, supervised by Qinghua Zhang and Laurent Mevel, 12/2023-11/2025.
- O A Shereena, postdoc at IIT Mandi, co-supervised by Laurent Mevel, since 09/2023.
- Julian Legendre, postdoc at Inria, co-supervised by Laurent Mevel, Jean Dumoulin and Thibaud Toullier, 09/2024–08/2025.
- Antoine Barré, research engineer, DIAM, supervised by Vincent Le Cam, 11/2024–10/2025.
- Nathanaël Gey, Junior Research Engineer in CityFAB CD92 project since 11/2024, co-supervised by Thibaud Toullier and Jean Dumoulin.

Internships

- M1: Hamza Majid, Nouhaila Raisse (ECN), Low-rank representation and Lattice Boltzmann Method for optical flow, supervised by Romain Noel, Vincent Baltazart and Michael Doehler, 11/2023–03/2024.
- M1: Yann Bouchereau (ENPC), Lattice Boltzmann simulations of supercooling effect, funded by Gustave Eiffel Foundation, supervised by Romain Noel, 02/2024 – 08/2024.
- M1: Alix Danvy (ENS Rennes), Development on OBLiX framework, supervised by Romain Noel and Thibaud Toullier, 11/2023 – 04/2024.

- M2: Ruining Chen (Mines St-Etienne), Evaluation of Liquid Tanks under seismic load, supervised by Romain Noel and Christophe Droz, 11/2023 – 04/2024.
- Nino Landormy (IMT Atlantique), Digitalizing an NDT measurement process for civil engineering operators, apprenticeship supervised by Vincent Baltazart, Romain Noel and Thibaud Toullier, 10/2023–09/2026.
- Nathanaël Gey (Mines Nantes), apprenticeship supervised by Jean Dumoulin, Thibaud Toullier, Mathias Malandain, Romain Noel, 09/2021–08/2024.
- Adji Toure (EC Nantes), embedded software for GERONIMO system, apprenticeship supervised by Arthur Bouche, 09/2022–08/2025.
- Jules Illand, BSc.3. Wave and vibration analysis of linear atomic chains, supervised by Christophe Droz, 05/2024–06/2024.
- Lucas Rouhi, MSc.2. Wave propagation analysis in metamaterials, supervised by Christophe Droz, 04/2024–08/2024.
- Benoit Senard, Relay-PhD. Periodic structure theory via Finite Element Modelling, supervised by Christophe Droz, 04/2024–09/2024.

9.2.3 Juries

- Christophe Droz
  - PhD Defense Examinator - Institut national des sciences appliquées. Diego Salam Claro, "Wave-based numerical approaches for non-destructive testing of structural assemblies involving straight waveguides and curved joints". Defense May 2024.
  - CSI member of PhD candidate Theo Gherdaoui, "Nonlinear small-time controllability results for multi-controlled systems", ENS Rennes, since 09/2022.
- Laurent Mevel, Qinghua Zhang
  - HDR Defense Examinators - Université de Rennes. Christophe Droz, "A Unified Wave Finite Element Modeling and Identification Framework for Periodic Structures: Towards Metamaterial Twins". Defense December 2 2024.
- Vincent Le Cam
  - PhD Defense Examinator, Université de Nantes, Walid Askri, "Générateurs flexibles hybrides piézo/tribo électrique pour l'auto-alimentation de capteurs communicants", defense 18/12/2024, and CSI member.

9.3 Popularization

9.3.1 Specific official responsibilities in science outreach structures

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

9.3.2 Productions (articles, videos, podcasts, serious games, ...)

- Christophe Droz gave three interviews in regional or national magazines. Articles have been published in:
  - Inria Emergences (May, 2024, "A New Concept for Acoustic Insulation in Transportation")
  - Sciences Ouest (June, 2024, "Atoms, Noise, and Waves: An Acoustic Challenge")
  - Usine Nouvelle (October, 2024, "Archi-Noise: towards low-frequency metamaterials")

9.3.3 Others science outreach relevant activities

- Michael Doehler has given a presentation at the Sci-Rennes seminar series at the Inria center of the University of Rennes (01/2024).
- Vincent Le Cam organizes the stay of high school students for internships on the UGE campus in Nantes.

10 Scientific production

10.1 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` (cit. on p. 14).

[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` (cit. on p. 14).

[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 (cit. on p. 13).

[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` (cit. on p. 14).

[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] P. Lair, J. Dumoulin and P. Millan. 'Inverse method for flux characterization using infrared thermography in die forging'. In: *Numerical Heat Transfer, Part A Applications* 33.3 (1998), pp. 267–277.

[11] 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`.

[12] 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` (cit. on pp. 15, 16).

[13] 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).

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

[15] Q. Zhang, M. Sorine and M. Admane. 'Inverse Scattering for Soft Fault Diagnosis in Electric Transmission Lines'. In: *IEEE Transactions on Antennas and Propagation* 59.1 (2011), pp. 141–148. URL: `https://hal.inria.fr/inria-00365991` (cit. on pp. 15, 16).

10.2 Publications of the year

International journals

[16] M. Al Bacha, M. L. Nguyen, P. Hornych, O. Chupin, J. Blanc and X. Chapeleau. 'Comparison of surface layers responses under heavy truck loadings on new and rehabilitated pavement with different interface bond conditions'. In: *Canadian journal of civil engineering* (1st Oct. 2024). DOI: `10.1139/cjce-2024-0105`. URL: `https://hal.science/hal-04836891` (cit. on p. 20).

[17] A. Cadoret, E. D. Goy, J.-M. Leroy, J.-L. Pfister and L. Mevel. 'Linear time periodic system approximation based on Floquet and Fourier transformations for operational modal analysis and damage detection of wind turbine'. In: *Mechanical Systems and Signal Processing* 212 (15th Apr. 2024), p. 111157. DOI: `10.1016/j.ymssp.2024.111157`. URL: `https://inria.hal.science/hal-04483449` (cit. on p. 25).

[18] A. Gavilán Rojas, Q. Zhang and C. Droz. 'A computationally efficient k(ω)-spectral form for partial dispersion analyses within the wave finite element framework'. In: *Journal of Sound and Vibration* 593 (22nd Dec. 2024), p. 118652. DOI: `10.1016/j.jsv.2024.118652`. URL: `https://hal.science/hal-04750240` (cit. on p. 22).

[19] C. Karakostas, G. Quaranta, E. Chatzi, A. C. Zülfikar, O. Çetindemir, G. de Roeck, M. Döhler, M. P. Limongelli, G. Lombaert, N. M. Apaydın, V. Pakrashi, C. Papadimitriou and A. Yeşilyurt. 'Seismic assessment of bridges through structural health monitoring: a state-of-the-art review'. In: *Bulletin of Earthquake Engineering* 22.3 (2024), pp. 1309–1357. DOI: `10.1007/s10518-023-01819-3`. URL: `https://inria.hal.science/hal-04488666` (cit. on p. 25).

[20] É. Lac, G. de Spiegeleer, A. Delsalle, F. Collonval, D.-T. Lê and M. Malandain. 'CoSApp: a Python library to create, simulate and design complex systems'. In: *Journal of Open Source Software* 9.94 (29th Feb. 2024), p. 6292. DOI: `10.21105/joss.06292`. URL: `https://inria.hal.science/hal-04823764` (cit. on p. 22).

[21] P. Leiva-Padilla, X. Chapeleau, M.-L. Nguyen, J. Blanc, S. Allam, E. Loison and P. Hornych. 'Use of Distributed Fiber Optic Sensors for the Monitoring of an Accelerated Pavement Test'. In: *Transportation Research Record* 2678.10 (14th Mar. 2024), pp. 131–146. DOI: `10.1177/03611981241231801`. URL: `https://hal.science/hal-04836946` (cit. on p. 20).

[22] A. Mélot, E. Denimal and L. Renson. 'Control of isolated response curves through optimization of codimension-1 singularities'. In: *Computers & Structures* (17th Apr. 2024), pp. 1–19. DOI: `10.1016/j.compstruc.2024.107394`. URL: `https://inria.hal.science/hal-04555084` (cit. on p. 23).

[23] A. Mélot, E. Denimal and L. Renson. 'Multi-parametric optimization for controlling bifurcation structures'. In: *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* (2024), pp. 1–22. DOI: `10.1098/rspa.2023.0505`. URL: `https://hal.science/hal-04378993` (cit. on p. 23).

[24] A. Mendler, M. Döhler and C. U. Grosse. 'Predictive probability of detection curves based on data from undamaged structures'. In: *Structural Health Monitoring* 23.3 (2024), pp. 1725–1741. DOI: `10.1177/14759217231193088`. URL: `https://inria.hal.science/hal-04557859` (cit. on p. 29).

[25] B. Merainani, B. Xiong, V. Baltazart, M. Döhler, J. Dumoulin and Q. Zhang. 'Subspace-based modal identification and uncertainty quantification from video image flows'. In: *Journal of Sound and Vibration* 569 (Jan. 2024), p. 117957. DOI: 10.1016/j.jsv.2023.117957. URL: https://inria.hal.science/hal-04436527 (cit. on pp. 18, 24).

[26] R. Noël, A. Renier-Robin and L. Navarro. 'Generalized Dithering using the Lattice Boltzmann Method'. In: *Signal, Image and Video Processing* 18.12 (20th Sept. 2024), pp. 8507–8523. DOI: 10.1007/s11760-024-03465-x. URL: https://hal.science/hal-04815444 (cit. on p. 21).

[27] J. Pan, H. Pan, M. Sun, Y. Wang, V. Baltazart, X. Dong, J. Zhao, X. Zhang and H. C. So. 'Co-prime Sampling based Time-Delay Estimation for Roadway Survey by Ground Penetrating Radar via Off-Grid Sparse Bayesian Learning'. In: *IEEE Transactions on Radar Systems* 2 (25th Sept. 2024), pp. 966–978. DOI: 10.1109/TRS.2024.3467993. URL: https://hal.science/hal-04714181 (cit. on p. 26).

[28] T. Toullier and J. Dumoulin. 'Bias and bottlenecks study in outdoor long term thermal monitoring by infrared thermography: Leveraging opportunistic data for temperature estimation'. In: *Infrared Physics and Technology* 141 (Sept. 2024), p. 105471. DOI: 10.1016/j.infrared.2024.105471. URL: https://inria.hal.science/hal-04677950 (cit. on p. 18).

[29] Z. Wang, Y. Ma, Q. Zhang, W. Tang and Y. Shen. 'Interval Estimation for Time-Varying Descriptor Systems via Simultaneous Optimizations of Multiple Interval Widths'. In: *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 54.6 (June 2024), pp. 3774–3782. DOI: 10.1109/TSMC.2024.3371677. URL: https://hal.science/hal-04842496 (cit. on p. 26).

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International peer-reviewed conferences

[31] N. Aswal, A. Mélot, L. Mevel and Q. Zhang. 'State reconstruction for stochastic nonlinear systems with unknown local nonlinearities via output injection'. In: *IFAC-PapersOnLine*. MICNON 2024 - 4th IFAC Conference of Modelling, Identification and Control of Nonlinear Systems. Vol. 58. 21. Lyon, France, 2024, pp. 256–261. DOI: 10.1016/j.ifacol.2024.10.222. URL: https://hal.science/hal-04765401 (cit. on p. 27).

[32] A. Coiret and V. Le Cam. 'Applicability of front-wheel braking procedure to evaluate road available grip'. In: CETRA 2024 - 8th International Conference on Road and Rail Infrastructure. Cavtat - Dubrovnik, Croatia, 2024, pp. 1–8. DOI: 10.5592/CO/cetra.2024.1536. URL: https://hal.science/hal-04598500.

[33] N. Delaplanque, S. Chataigner, M. Quiertant, K. Benzarti, A. Rolland, X. Bourbon, X. Chapeleau, L. Battais and L. Gaillet. 'Investigations on the ageing of GFRP rebar-concrete bond under sustained load for a high strength concrete'. In: *Procedia Structural Integrity*. SMAR 2024 – 7th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures. Vol. 64. SMAR 2024 – 7th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures. Salerno, Italy, 8th Nov. 2024, pp. 1492–1499. DOI: 10.1016/j.prostr.2024.09.399. URL: https://enpc.hal.science/hal-04776381 (cit. on p. 20).

[34] J. Dumoulin, B. Merainani and T. Toullier. 'Study of hot box detection on moving targets using way side thermal infrared camera and image processing methods : application to railway infrastuctures'. In: European Geosciences Union. Vienne, Austria, 9th Mar. 2024, pp. 1–2. DOI: 10.5194/egusphere-egu24-16481. URL: https://inria.hal.science/hal-04798431 (cit. on p. 19).

[35] A. Fawaz, E. Lepretre, X. Chapeleau and S. Chataigner. 'Development and Validation of a Creep Frame Adapted for ELS (End Load Split) Test'. In: *Procedia Structural Integrity*. SMAR 2024 – 7th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures. Vol. 64. Salerno, Italy: Elsevier, 2024, pp. 89–96. DOI: 10.1016/j.prostr.2024.09.216. URL: https://hal.science/hal-04836980 (cit. on p. 20).

[36] E. Gennesseaux, D. Vizzari, J. Dumoulin, E. Chailleux, S. Lavaud, J.-L. Manceau and T. Sedran. 'Laboratory and full-scale experiment of a novel hybrid system to harvest energy through concrete pavement'. In: ICCP 2024 - 13th International Conference on Concrete Pavements. Minneapolis, United States, 2024. URL: `https://univ-eiffel.hal.science/hal-04723731` (cit. on p. 19).

[37] S. Gres, M. Döhler, V. Dertimanis and E. Chatzi. 'Data-Driven Identification of Noise Covariances in Kalman Filtering for Virtual Sensing Applications'. In: *Proceedings of the 10th International Operational Modal Analysis Conference (IOMAC 2024)*. IOMAC 2024 - 10th International Operational Modal Analysis Conference. Vol. 515. Lecture Notes in Civil Engineering. Naples, Italy: Springer Nature Switzerland, 22nd June 2024, pp. 375–382. DOI: `10.1007/978-3-031-61425-5_36`. URL: `https://inria.hal.science/hal-04639377` (cit. on p. 24).

[38] S. Gres, K. E. Tatsis, M. Döhler, V. Dertimanis and E. Chatzi. 'Rejection of parametric model errors in a recursive Kalman filter for virtual sensing applications'. In: EWSHM 2024 - 11th European Workshop on Structural Health Monitoring. Vol. 29. 7. Potsdam, Germany, July 2024, pp. 1–8. DOI: `10.58286/29694`. URL: `https://inria.hal.science/hal-04639385` (cit. on p. 27).

[39] F. Hashemniya, B. Caillaud, E. Frisk, M. Krysander and M. Malandain. 'Fault Diagnosability Analysis of Multi-Mode Systems'. In: SAFEPROCESS 2024 - 12th IFAC Symposium on Fault Detection, Supervision and Safety for Technical Processes. Vol. 58. 4. Ferrara, Italy: Elsevier, 2024, pp. 210–215. DOI: `10.1016/j.ifacol.2024.07.219`. URL: `https://inria.hal.science/hal-04803147` (cit. on p. 28).

[40] M. Kabbara, X. Chapeleau, Q. Zhang and F. Bourquin. 'Numerical evaluation of strain transfer model for steel-reinforced optical fiber cable embedded in a cylindrical concrete beam with two void inclusions'. In: *EPJ Web Conferences*. AOP 2024 - 6th International Conference on Applications of Optics and Photonics. Vol. 305. Aveiro, Portugal, 15th Oct. 2024, p. 00021. DOI: `10.1051/epjconf/202430500021`. URL: `https://hal.science/hal-04836439` (cit. on p. 19).

[41] Z. Luo, B. Merainani, M. Döhler, V. Baltazart and Q. Zhang. 'Vision-based operational modal analysis robust to environmental conditions'. In: *Proceedings of the 10th International Operational Modal Analysis Conference (IOMAC 2024)*. IOMAC 2024 - 10th International Operational Modal Analysis Conference. Naples, Italy, 2024, pp. 1–8. DOI: `10.1007/978-3-031-61425-5_66`. URL: `https://inria.hal.science/hal-04598198` (cit. on pp. 18, 24).

[42] V. Mahé, A. Mélot, B. Chouvion and C. Droz. 'Computing the dynamic response of a periodic structure coupled with a nonlinear junction using the harmonic balance method and Floquet-Bloch modelling'. In: INTER-NOISE 2024 - 53rd International Congress and Exposition on Noise Control Engineering. Vol. 270. 6. Nantes, France, 4th Oct. 2024, pp. 5622–5628. DOI: `10.3397/IN_2024_3623`. URL: `https://hal.science/hal-04829390` (cit. on p. 22).

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[44] A. Mélot, E. Denimal Goy and L. Renson. 'On the use of bifurcation curves for system identification and model updating purposes'. In: ECCOMAS 2024 - 9th European Congress on Computational Methods in Applied Sciences and Engineering. Lisbon, Portugal, 6th June 2024, pp. 1–1. URL: `https://hal.science/hal-04701324` (cit. on p. 28).

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[53] J. Priou, A. Mendler, M. Perrault, L. Guerineau and M. Döhler. ‘Normalization of Environmental Effects in Modal Parameter Tracking’. In: *Proceedings of the 10th International Operational Modal Analysis Conference (IOMAC 2024)*. IOMAC 2024 - 10th International Operational Modal Analysis Conference. Vol. 515. Lecture Notes in Civil Engineering. Naples, Italy: Springer Nature Switzerland, 22nd June 2024, pp. 95–102. DOI: `10.1007/978-3-031-61425-5_10`. URL: `https://inria.hal.science/hal-04639381` (cit. on p. 24).

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