SISTHEM

Statistical **I**nference for **ST**ructural **HE**alth **M**onitoring

Inférence Statistique pour la Surveillance d'Intégrité de Structures

Proposal for a joint Cnrs - Inria - U. Rennes 1 project-team* at Irisa (Rennes)

5th April 2004

Priority: Coupling models and data to monitor and diagnose complex systems.

Research:

Monitoring, system identification, change detection, diagnostics:
On-line identification and detection algorithms, subspace-based algorithms,
Statistical hypotheses testing,
Sensors fusion,
Optimal sensors placement.

Applications:

Vibration-based structural analysis and damage detection and localization:

Monitoring the integrity of the civil and transportation infrastructures,
handling environmental effects.

Clearing aircrafts from instabilities, in-flight test data analysis,
flutter monitoring.

*Expected preferably within the *new* Inria 4C program.

Contents

1 The team

1.1 People

Michèle Basseville	DR CNRS	Team head
Laurent Mevel	CR INRIA	Team member
Albert Benveniste	DR INRIA	Team member, part time[1]
Maurice Goursat	DR INRIA	Team member, part time[2]
Houssein Nasser	Ph.D. student	MENJR/ACI SI fund, since Oct. 1, 2003
Auguste Sam	Technical staff	INRIA FliTE contract, until Feb. 29, 2004
Huguette Béchu	TR INRIA	Team assistant, shared with ASPI, DISTRIBCOM, S4

Houssein Nasser is a Ph.D. student within the civil engineering research axis (sections 4.2 and 6.2.2).

A Ph.D. student should have started in October 2003 within the aerodynamics research axis (sections 4.3 and 6.2.2), but the industrial partner finally decided to postpone the research investigation and funding.

1.2 Biographical sketch

- Michèle Basseville is graduated from the former Mathematics section of the École Normale Supérieure de Fontenay-aux-Roses and from the Statistics department of the Université de Paris-Sud at Orsay. She has been CNRS researcher since 1976, and research director since 1990.
- Laurent Mevel is graduated from University of Rennes 1 in 1997, where he received a Ph.D. in Applied Mathematics in the field of statistical inference for hidden Markov models, which has also been the topic of his post-doc at Padova, I. In 1998-1999, he spent about 1.5 year at LMS, Leuven, B., for developping and adapting damage detection techniques for the special problem of mechanical engeneering and monitoring of civil structures. Then, he has been INRIA researcher since 2000. Now he is working on identification and detection of partially hidden stochastic systems, including Markov process and linear systems.

1.3 History and background

Identification and change detection and monitoring of dynamical systems have been among the main research topics of the project SIGMA2 and the former project AS [2, 1]. The first investigations of the senior team members on modal analysis and vibration monitoring have been initiated upon a regional solicitation and trace back to the early eighties. Several Ph.D. theses have been devoted to those topics [97, 98, 95, 94]. The investigation of different application examples [29, 5] has been conducted through contracts with two main partners (IFREMER and EDF).

[1] Head of DISTRIBCOM and member of S4.
[2] Head of METALAU, Rocquencourt.

After a fruitful cooperation with AS&I-Dataid (Lyon), which however did not end up with knowledge and software transfer, contacts with LMS International[3] have been established. The actual cooperation started with the Eurêka project SINOPSYS (1996-1999). This has provided us with the opportunity of both a theoretical and numerical revisit of our vibration monitoring algorithms, and the investigation of new application examples, among which several examples within the civil engineering and aeronautics areas. This in turn resulted in the early formulation of new research challenges.

During that period, Laurent Mevel has spent about 1.5 year at LMS as an engineer, after a Ph.D. thesis on the statistics of hidden Markov models [96], which has also been the topic of his post-doc [23]. A major event for the continuation of the vibration monitoring research activity has been his recruitment as an INRIA researcher by the end of 1999.

During the evaluation of the former INRIA 4A program in 2000, SIGMA2 indicated that the investigation of the new research challenges would depend on the establishment of relevant cooperations. Since that time, strong partnerships have been established in the two domains, civil engineering and aeronautics. This is, in our mind, the reason why this research activity now deserves the launching of a dedicated project.

2 Context and major objectives

2.1 Context

Structural Health Monitoring (SHM) is the whole process of the design, development and implementation of techniques for the detection, localization and estimation of damages, for monitoring the integrity of structures and machines within the aerospace, civil and mechanical engineering infrastructures [135, 121, 128, 130]. In addition to these key driving application areas, SHM is now spreading over most transportation infrastructures and vehicles, within the naval, railway and automobile domains. Examples of structures or machines to be monitored include aircrafts, spacecrafts, buildings, bridges, dams, ships, offshore platforms, on-shore and off-shore wind farms (wind energy systems), turbo-alternators and other heavy machinery, ...

The emergence of stronger safety and environmental norms, the need for early decision mechanisms, together with the widespread diffusion of sensors of all kinds, result in a thorough renewal of sensor information processing problems. This calls for new research investigations within the sensor data (signal and image) information processing community. In particular, efficient and robust methods for structural analysis, non destructive evaluation, integrity monitoring, damage diagnostics and localization, are necessary for fatigue and aging prevention, and for condition-based maintenance. Moreover, multidisciplinary research, mitigating information science, engineering science and scientific computing, is mandatory. However, most of the SHM research investigations are conducted within mechanical, civil and aeronautical engineering departments, with little involvement of advanced data information processing specialists.

The growth of both the needs for and the research on SHM has lead to the launching of :

- New series of international workshops, with the aim of identifying critical and strategic research issues and specific projects to be jointly investigated :
  - The International Workshop on SHM in Stanford every two years since 1997, `http://structure.stanford.edu/workshop/`,

[3] **L**euven **M**easurement **S**ystems, one of the two engineering solutions provider world leaders in that field – `http://www.lmsintl.com`

- The European Workshop on SHM every two years since 2002, following the European COST F3 conference in Madrid in 2000, `http://www.shm-europe.net`,
- The International Workshop on Advanced Sensors, SHM and Smart Structures initiated in 2003, `http://www.mita.sd.keio.ac.jp/news/workshop/workshop.htm`,

in addition to a Theme Topic [139] at the *International Modal Analysis Conference* `http://www.sem.org/index.asp` : SHM is the Technical Theme of the 2005 edition.

- A new journal *Structural Health Monitoring, An International Journal*, created in 2002.
- Research actions and programs :
  - The NSF project NEES, which will be completed by October 2004, `http://www.eng.nsf.gov/nees/`,
  - The NIED-Miki E-DEFENSE, `http://www.bosai.go.jp/sougou/sanjigen/`,
  - The NSF project 03-512 *Sensors and Sensor Networks*, `http://nsf.gov/pubsys/ods/`, March 2003 call for proposals. One of the three topical areas is entitled *Interpretation, Decision and Action Based on Sensor Data*. Examples include development of new statistical algorithms, concepts for optimal sensors location for effective process/system control, health monitoring systems for civil structures.
  - The NSF-FHWA project on *Advancing States of the Art and Practice of Engineering and Management of the Highway Transportation Infrastructure*.
  - The COST action F3 *Dynamique des Structures*, with a *Health Monitoring* Working Group, `http://www.ulg.ac.be/ltas-vis/costf3/costf3.html`.

Even though some differences exist between the two main application domains, civil engineering and aeronautics, a common feature of the SHM research activity is that it is less developed and supported in Europe (except in Great Britain, Italy and Greece) than in America (US, Canada) and in Asia (Japan, and also China). Moreover, the French research effort on these issues has not yet been sufficiently developed, compared with the associated scientific and socio-economic challenges.

2.2 Objectives

In this context, and based on our background and results on model-based statistical identification, change detection and vibration monitoring described below, our objectives are :

- Importing knowledge from engineering communities within our model-based information processing methods;
- Mitigating statistical inference tools (identification, detection, rejection) with simplified and/or reduced models of aerodynamical effects, thermodynamical or other environmental effects;
- Involving nonlinearities in the models, algorithms and proofs of performances;
- Exporting our data information processing algorithms within the structural health monitoring community, based on specific training actions, on a dedicated free SCILAB toolbox, and an industrial software.

Before describing our research program, we introduce key elements of the scientific foundations of our work, and some key features of our two main application domains. This is done in sections 3 and 4, respectively.

3 Scientific foundations

The team members and collaborators all have a background on several, if not all, of the research topics listed on the first page. In this section, the main features for the key monitoring issues, namely identification, detection, and diagnostics, are provided, and a particular instantiation relevant for vibration monitoring is described.

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

3.1 Identification

The continuous system behavior 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 $\theta \in \Theta$. An *estimating function*, for example of the form :

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

is such that $\mathbf{E}_\theta[\mathcal{K}_N(\theta)] = 0$ for all $\theta \in \Theta$. In many situations, $\mathcal{K}$ is the gradient of a function to be minimized : squarred prediction error, log-likelihood (up to a sign), ... For performing model identification on the basis of observations $(Z_0, \ldots, Z_N)$, an estimate of the unknown parameter is then [112, 106, 89] :

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

Assuming that θ^* is the true parameter value, and that $\mathbf{E}_{\theta^*}[\mathcal{K}_N(\theta)] = 0$ if and only if $\theta = \theta^*$ with θ^* fixed (identifiability condition), then $\widehat{\theta}_N$ converges towards θ^*. From the central limit theorem, the vector $\mathcal{K}_N(\theta^*)$ is asymptotically Gaussien with zero mean, with covariance matrix Σ which can be either computed or estimated. If, additionally, the matrix $\mathcal{J}_N = -\mathbf{E}_{\theta^*}[\mathcal{K}'_N(\theta^*)]$ is invertible,

then using a Taylor expansion and the constraint $\mathcal{K}_N(\widehat{\theta}_N) = 0$, the asymptotic normality of the estimate is obtained :

$$\sqrt{N}\,(\widehat{\theta}_N - \theta^*) \approx \mathcal{J}_N^{-1}\,\sqrt{N}\,\mathcal{K}_N(\theta^*)$$

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

- *Recursive estimation :* This is the capability to compute $\widehat{\theta}_{N+1}$ simply from $\widehat{\theta}_N$ – this can be achieved with the aid of some approximations which price must be one order of magnitude lower than the estimation error $1/\sqrt{N}$;
- *Adaptive estimation :* This is the capability to *track* the true parameter vector θ^* when it is time-varying.

3.2 Detection

Our approach to on-board detection is based on the so-called asymptotic statistical local approach [114, 110], which we have extended and adapted [17, 2, 1, 14, 31]. It is worth noticing that these investigations of ours have been initially motivated by a vibration monitoring application example [9, 7, 30, 98]. It should also be stressed that, as opposite to many monitoring approaches, our method does not require repeated identification for each newly collected data sample.

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

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

These indicators are computationally cheap, and thus can be embedded. This is of particular interest in some applications, such as flutter monitoring, as explained in 4.3.

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

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

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

The behavior of the monitored system is again assumed to be described by a parametric model $\{\mathbf{P}_\theta\,,\,\theta \in \Theta\}$, and the safe behavior of the process is assumed to correspond to the parameter value θ_0. This parameter often results from a preliminary identification based on reference data, as in 3.1.

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

$$(\textit{Safe})\ \mathbf{H}_0 :\ \theta = \theta_0 \quad \text{and} \quad (\textit{Damaged})\ \mathbf{H}_1 :\ \theta = \theta_0 + \eta/\sqrt{N} \tag{1}$$

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

$$\zeta_N = 1/\sqrt{N}\ \sum_{k=0}^{N} K(\theta_0, Z_k) = \sqrt{N}\ \mathcal{K}_N(\theta_0)\ . \tag{2}$$

If the matrix $\mathcal{J}_N = -\,\mathbf{E}_{\theta_0}[\mathcal{K}'_N(\theta_0)]$ converges towards a limit $\mathcal{J}$, then the central limit theorem shows [89] that the residual is asymptotically Gaussian :

$$\zeta_N \xrightarrow[N \to \infty]{} \begin{cases} \mathcal{N}(0, \Sigma) & \text{under } \mathbf{P}_{\theta_0}\ , \\ \mathcal{N}(\mathcal{J}\,\eta, \Sigma) & \text{under } \mathbf{P}_{\theta_0 + \eta/\sqrt{N}}\ , \end{cases} \tag{3}$$

where the asymptotic covariance matrix Σ can be estimated [31, 85], and manifests the deviation in the parameter vector by a change in its own mean value. Then, deciding between $\eta = 0$ and $\eta \neq 0$ amounts to compute the following χ^2-test, provided that $\mathcal{J}$ is full rank and Σ is invertible :

$$\chi^2 = \overline{\zeta}^T\, \mathbf{F}^{-1}\, \overline{\zeta} \gtrless \lambda\ . \tag{4}$$

where $\overline{\zeta} \triangleq \mathcal{J}^T\, \Sigma^{-1}\, \zeta_N$ and $\mathbf{F} \triangleq \mathcal{J}^T\, \Sigma^{-1}\, \mathcal{J}$.

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

3.3 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 described in 3.3.1. How this relates to diagnostics is then addressed in 3.3.2.

3.3.1 Isolation

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 [12]. Here we only sketch two intuitively simple statistical nuisance elimination techniques, which proceed by projection and rejection, respectively.

The fault vector η is partitioned into an informative part and a nuisance part, and the sensitivity matrix $\mathcal{J}$, the Fisher information matrix $\mathbf{F} = \mathcal{J}^T\, \Sigma^{-1}\, \mathcal{J}$ and the normalized residual $\overline{\zeta} = \mathcal{J}^T\, \Sigma^{-1}\, \zeta_N$ are partitioned accordingly

$$\eta = \begin{pmatrix} \eta_a \\ \eta_b \end{pmatrix}\ , \quad \mathcal{J} = \begin{pmatrix} \mathcal{J}_a & \mathcal{J}_b \end{pmatrix}\ , \quad \mathbf{F} = \begin{pmatrix} \mathbf{F}_{aa} & \mathbf{F}_{ab} \\ \mathbf{F}_{ba} & \mathbf{F}_{bb} \end{pmatrix}\ , \quad \overline{\zeta} = \begin{pmatrix} \overline{\zeta}_a \\ \overline{\zeta}_b \end{pmatrix}\ .$$

A rather intuitive statistical solution to the isolation problem, which can be called *sensitivity* approach, consists in projecting the deviations in η onto the subspace generated by the components η_a to be isolated, and deciding between $\eta_a = \eta_b = 0$ and $\eta_a \neq 0$, $\eta_b = 0$. This results in the following test statistics :

$$t_a = \overline{\zeta}_a^T \, \mathbf{F}_{aa}^{-1} \, \overline{\zeta}_a \ , \tag{5}$$

where $\overline{\zeta}_a$ is the partial residual (score). If $t_a \geq t_b$, the component responsible for the fault is considered to be a rather than b. This approach is a particular case of a more general one [12].

Another statistical solution to the problem of isolating η_a consists in viewing parameter η_b as a nuisance, and using an existing method for inferring part of the parameters while ignoring and being robust to the complementary part. This method is called *min-max approach*. It consists in replacing the nuisance parameter component η_b by its least favorable value, for deciding between $\eta_a = 0$ and $\eta_a \neq 0$, with η_b unknown. This results in the following test statistics :

$$t_a^* = \overline{\zeta}_a^{*T} \, \mathbf{F}_a^{*-1} \, \overline{\zeta}_a^* \ , \tag{6}$$

where $\overline{\zeta}_a^* \triangleq \overline{\zeta}_a - \mathbf{F}_{ab} \, \mathbf{F}_{bb}^{-1} \, \overline{\zeta}_b$ is the effective residual (score) resulting from the regression of the informative partial score $\overline{\zeta}_a$ over the nuisance partial score $\overline{\zeta}_b$, and where the Schur complement $\mathbf{F}_a^* = \mathbf{F}_{aa} - \mathbf{F}_{ab} \, \mathbf{F}_{bb}^{-1} \, \mathbf{F}_{ba}$ is the associated Fisher information matrix. If $t_a^* \geq t_b^*$, the component responsible for the fault is considered to be a rather than b.

The properties of and relationships between these two types of tests are investigated in [13].

3.3.2 Diagnostics

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 in section 3.4, 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 [7].

Our approach to the latter diagnosis problem is basically a detection approach again, and not a (generally ill-posed) inverse problem estimation approach [17, 94, 5, 10]. The basic idea is to note that the physical sensitivity matrix writes $\mathcal{J} \, \mathcal{J}_{\Phi\theta}$, where $\mathcal{J}_{\Phi\theta}$ is the Jacobian matrix at Φ_0 of the application $\Phi \mapsto \theta(\Phi)$, and to use the sensitivity test (5) for the components of the parameter vector Φ. Typically this results in the following type of directional test :

$$\chi_\Phi^2 = \zeta^T \, \Sigma^{-1} \, \mathcal{J} \, \mathcal{J}_{\Phi\theta} \, (\mathcal{J}_{\Phi\theta}^T \, \mathcal{J}^T \, \Sigma^{-1} \, \mathcal{J} \, \mathcal{J}_{\Phi\theta})^{-1} \, \mathcal{J}_{\Phi\theta}^T \, \mathcal{J}^T \, \Sigma^{-1} \, \zeta \overset{>}{<} \lambda \ . \tag{7}$$

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

As a summary, the machinery in 3.1, 3.2 and 3.3 provides us with a generic framework for designing monitoring algorithms for continuous structures, machines and processes. This approach assumes that a model of the monitored system is available. This is a reasonable assumption within the field of applications described in section 4, since most mechanical processes rely on

physical principles which write in terms of equations, providing us with models[4]. As explained in section 6, these important *modeling* and *parameterization* issues are among the questions we intend to investigate within our research program.

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

3.4 Subspace-based identification and detection

For reasons closely related to the vibrations monitoring applications described in section 4, we have been investigating subspace-based methods, for both the identification and the monitoring of the eigenstructure (λ, ϕ_λ) of the state transition matrix F of a linear dynamical state-space system :

$$\left\{ \begin{array}{rcl} X_{k+1} & = & F\ X_k + V_{k+1} \\ Y_k & = & H\ X_k \end{array} \right. , \tag{8}$$

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

$$\det\ (F - \lambda\ I) = 0, \quad (F - \lambda\ I)\ \phi_\lambda = 0, \quad \varphi_\lambda \triangleq H\ \phi_\lambda \tag{9}$$

The (canonical) parameter vector in that case is :

$$\theta \triangleq \left(\begin{array}{c} \Lambda \\ \mathrm{vec}\Phi \end{array} \right) \tag{10}$$

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 [117]. A contribution of ours, minor but extremely fruitful, has been to write the output-only covariance-driven subspace identification method under a form which involves a parameter estimating function, from which we define a *residual adapted to vibration monitoring* [4]. This is explained next.

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

$$\mathcal{H}_{p+1,q} \triangleq \left(\begin{array}{cccc} R_0 & R_1 & \vdots & R_{q-1} \\ R_1 & R_2 & \vdots & R_q \\ \vdots & \vdots & \vdots & \vdots \\ R_p & R_{p+1} & \vdots & R_{p+q-1} \end{array} \right) \triangleq \mathrm{Hank}\,(R_i) \tag{11}$$

be the output covariance and Hankel matrices, respectively; and: $G \triangleq \mathbf{E}\left(X_k Y_k^T\right)$ Direct computations of the R_i's from the equations (8) lead to the well known [116] key factorizations :

$$R_i = H F^i G \tag{12}$$

$$\mathcal{H}_{p+1,q} = \mathcal{O}_{p+1}(H, F)\ \mathcal{C}_q(F, G) \tag{13}$$

[4]When physical models are either too complex or even not known at all, semi-physical or black-box models can be used instead [31].

where:

$$\mathcal{O}_{p+1}(H,F) \triangleq \begin{pmatrix} H \\ HF \\ \vdots \\ HF^p \end{pmatrix} \quad \text{and} \quad \mathcal{C}_q(F,G) \triangleq (G \; FG \; \cdots \; F^{q-1}G) \tag{14}$$

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 (9).

Since the actual model order is generally not known, this procedure is run with increasing model orders; this is discussed further in section 6.2.1.

Model parameter characterization. Choosing the eigenvectors of matrix F as a basis for the state space of model (8) yields the following representation of the observability matrix:

$$\mathcal{O}_{p+1}(\theta) = \begin{pmatrix} \Phi \\ \Phi\Delta \\ \vdots \\ \Phi\Delta^p \end{pmatrix} \tag{15}$$

where $\Delta \triangleq \text{diag}(\Lambda)$, and Λ and Φ are as in (10). Whether a nominal parameter θ_0 fits a given output covariance sequence $(R_j)_j$ is characterized by [129, 4]:

$$\mathcal{O}_{p+1}(\theta_0) \;\text{ and }\; \mathcal{H}_{p+1,q} \;\text{ have the same left kernel space.} \tag{16}$$

This property can be checked as follows. From the nominal θ_0, compute $\mathcal{O}_{p+1}(\theta_0)$ using (15), and perform e.g. a singular value decomposition (SVD) of $\mathcal{O}_{p+1}(\theta_0)$ for extracting a matrix U such that: $U^T\, U = I_s$ and $U^T\, \mathcal{O}_{p+1}(\theta_0) = 0$. Matrix U is not unique (two such matrices relate through a post-multiplication with an orthonormal matrix), but can be regarded as a function of θ_0. Then the characterization writes:

$$U(\theta_0)^T\, \mathcal{H}_{p+1,q} = 0 \tag{17}$$

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

$$\widehat{\mathcal{H}}_{p+1,q} \triangleq \text{Hank}\left(\widehat{R}_i\right), \quad \widehat{R}_i \triangleq 1/(N-i) \sum_{k=i+1}^{N} Y_k\, Y_{k-i}^T \tag{18}$$

and to define the residual vector:

$$\zeta_N(\theta_0) \triangleq \sqrt{N}\; \text{vec}\left(U(\theta_0)^T\, \widehat{\mathcal{H}}_{p+1,q}\right) \tag{19}$$

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 (17), we know that $\zeta_N(\theta_0)$ has zero mean when no change occurs in θ, and nonzero mean if a change occurs. Thus $\zeta_N(\theta_0)$ plays the role of a residual.

It is our experience that this residual has highly interesting properties, both for damage detection [4] and localization [10, 87], and for flutter monitoring [20, 91].

Other uses of the key factorizations. Factorization (13) is the key for a characterization of the canonical parameter vector θ in (10), and for deriving the residual. Factorization (12) is also the key for :

- Proving consistency and robustness results [18, 49, 51];
- Designing an extension of covariance-driven subspace identification algorithm adapted to the presence and fusion of non-simultaneously recorded multiple sensors setups [19];
- Proving the consistency and robustness of this extension [22];
- Designing various forms of *input-output* covariance-driven subspace identification algorithm adapted to the presence of both known (controlled) inputs and unknown (ambient) excitations [21].

4 Application domains

In this section, the problems we are faced with vibration-based monitoring and within our two major application domains are briefly described.

4.1 Vibrations-based monitoring

Detecting and localizing damages for monitoring the integrity of structural and mechanical systems is a topic of growing interest, due to the aging of many engineering constructions and machines and to increased safety norms. Many current approaches still rely on visual inspections or *local* non destructive evaluations performed manually. This includes acoustic, ultrasonic, radiographic or eddy-current methods; magnet or thermal field techniques, ... These experimental approaches assume an *a priori* knowledge and the accessibility of a neighborhood of the damage location.

Automatic *global* vibration-based monitoring techniques have been recognized to be useful alternatives to those local evaluations [120, 121, 151]. However this has led to actual damage monitoring systems only in the field of rotating machines [128].

A common feature of the structures to be monitored (e.g. civil engineering structures subject to hurricanes or earthquakes, but also swell, wind and rain; aircrafts subject to strength and turbulences, ...) is the following. These systems are subject to both fast and unmeasured variations in their environment and small slow variations in their vibrating characteristics. The available data (measurements from e.g. strain gauges or accelerometers) do not separate the effects of the external forces from the effect of the structure. The external forces vary more rapidly than the structure itself (fortunately !), damages or fatigues on the structure are of interest, while any change in the excitation is meaningless. Expert systems based on a human-like exploitation of recorded spectra can hardly work in such a case : the changes of interest (1% in eigenfrequencies) are visible neither on the signals nor on their spectra. A global health monitoring method must rather rely on a model which will help in discriminating between the two mixed causes of the changes that are contained in the measurements.

Classical modal analysis and vibration monitoring methods basically process data registered either on test beds or under specific excitation or rotation speed conditions. However there is a need for vibration monitoring algorithms devoted to the processing of data recorded in-operation, namely during the actual functioning of the considered structure or machine, without artificial excitation, speeding down or stopping.

Health monitoring techniques based on processing vibration measurements basically handle two types of characteristics: the *structural parameters* (mass, stiffness, flexibility, damping) and the *modal parameters* (modal frequencies, and associated damping values and mode-shapes); see [125, 120, 113] and references therein. A central question for monitoring is to compute *changes* in those characteristics and to assess their *significance*. For the *frequencies*, crucial issues are then: how to compute the changes, to assess that the changes are significant, to handle *correlations* among individual changes. A related issue is how to compare the changes in the frequencies obtained from experimental data with the sensitivity of modal parameters obtained from an analytical model. Furthermore, it has been widely acknowledged that, whereas changes in frequencies bear useful information for damage *detection*, information on changes in (the curvature of) mode-shapes is mandatory for performing damage *localization*. Then, similar issues arise for the computation and the significance of the changes. In particular, assessing the significance of (usually small) changes in the mode-shapes, and handling the (usually high) correlations among individual mode-shape changes are still considered as opened questions [125, 120, 113, 121].

Controlling the computational complexity of the processing of the collected data is another standard monitoring requirement, which includes a limited use of an analytical model of the structure. Moreover, the reduction from the analytical model to the experimental model (truncated modal space) is known to play a key role in the success of model-based damage detection and localization [125, 118].

The approach which we have been developing, based on the foundations in section 3, aims at addressing all the issues and overcoming the limitations above.

4.2 Civil engineering

Civil engineering is a currently renewing scientific research area, which can no longer be restricted to the single mechanical domain, with numerical codes as its central focus. Recent and significant advances in physics and physical chemistry have improved the understanding of the detailed mechanisms of the constitution and the behavior of various materials (see e.g. the multi-disciplinary general agreement CNRS-Lafarge). Moreover, because of major economical and societal issues, such as durability and safety of infrastructures, buildings and networks, civil engineering is evolving towards a multi-disciplinary field, involving in particular information sciences and technologies and environmental sciences.

These last ten years, monitoring the integrity of the civil infrastructure has been an active research topic, including in connected areas such as automatic control, for mastering either the aging of the bridges, as in America (US, Canada) and Great Britain, or the resistance to seismic events and the protection of the cultural heritage, as in Italy and Greece. The research effort in France seems to be more recent, maybe because a tendency of long term design without fatigue oriented inspections, as opposite to less severe design with planned mid-term inspections. One of the current thematic priorities of the Réseau de Génie Civil et Urbain (one of the first *réseaux de recherche technologique* - RGCU) is devoted to constructions monitoring and diagnostics. A recent workshop on *Auscultation, diagnostic et évaluation des ouvrages* organized on November 25-26, 2003 on request of the Direction de la Recherche (DRAST) of the Ministère de l'Équipement brought together about 170 persons, involved nine end-users needs presentations, and repeatedly stated that diagnostic is now the most important topic in civil engineering, together with residual life evaluation.

The picture in Asia (Japan, and also China) is somewhat different, in that the demand for automatic data processing for global SHM systems is much higher, because recent or currently built bridges are equipped with hundreds if not thousands of sensors; see e.g. `http://www.hyd.gov.hk/road/Projects/`, in particular the Hong Kong-Shenzen Western Corridor and Stonecutter Bridge projects.

The reasons why a bridge health monitoring system is needed are for [144] :

- Monitoring structural performance and applied loads;
- Facilitating the planning of inspection and maintenance;
- Validating design assumptions and parameters;
- Updating and revising design manuals and standards.

Among the challenges for vibration-based bridges health monitoring [131], two major issues are the different kinds of (non measured) excitation sources and the environmental effects [141, 126, 143]. Typically the traffic on *and* under the bridge, the wind and also the rain, contribute to excite the structure, and influence the measured dynamics. Moreover, the temperature is also known to affect the eigenfrequencies and mode-shapes, to an extent which is significant w.r.t. the deviations to be monitored.

As explained in section 6.2.2, one part of our research program is aimed at addressing these issues.

4.3 Aeronautics

The aging of aerospace structures is a major current concern of civilian and military aircraft operators. Another key driving factor for SHM is to increase the operation and support efficiency of an air vehicle fleet [128]. A SHM system is viewed as a component of a global integrated vehicle health management (IVHM) system. Overviews of the users needs can be found in [138, 132].

Improved safety and performance and reduced aircraft development and operating costs are other major concerns. One of the critical design objectives is to clear the aircraft from unstable aero-elastic vibrations (flutter) in all flight conditions. This requires a careful exploration of the dynamical behavior of the structure subject to vibration and aero-servo-elastic forces. This is achieved via a combination of ground vibration tests and in-flight tests. For both types of tests, various sensors data are recorded, and modal analyses are performed. Important challenges of the in-flight modal analyses are the limited choices for measured excitation inputs, and the presence of unmeasured natural excitation input (turbulence). A better exploitation of flight test data can be achieved by using output-only system identification methods, which exploits data recorded under natural excitation conditions (e.g., turbulent), without resorting to artificial control surface excitation and other types of excitation inputs [6, 76].

A crucial issue is to ensure that the newly designed airplane is stable throughout its operating range. A critical instability phenomenon, known under the name of *"aero-elastic flutter, involves the unfavorable interaction of aerodynamic, elastic, and inertia forces on structures to produce an unstable oscillation that often results in structural failure"* [147]. For preventing from this phenomenon, the airplane is submitted to a flight flutter testing procedure, with incrementally increasing altitude and airspeed. The problem of predicting the speed at which flutter can occur

is usually addressed with the aid of identification methods achieving modal analysis from the in-flight data recorded during these tests [147, 145, 142, 123]. The rationale is that the damping coefficient reflects the rate of increase or decrease in energy in the aero-servo-elastic system, and thus is a relevant measure of stability. Therefore, while frequencies and mode-shapes are usually the most important parameters in structural analysis, the most critical ones in flutter analysis are the damping factors, for some critical modes. The mode-shapes are usually not estimated for flutter testing [142].

Until the late nineties, most approaches to flutter clearance have led to *data-based* methods, processing different types of data [123]. A *combined data-based and model-based* method has been introduced recently under the name of flutterometer [148, 124]. Based on an aero-elastic state-space model and on frequency-domain transfer functions extracted from sensor data under controlled excitation, the flutterometer computes on-line a robust flutter margin using the μ-method for analyzing the worst case effects of model uncertainty. In recent comparative evaluations using simulated and real data [119, 123], several data-based methods are shown to fail in accurately predicting flutter when using data from low speed tests, whereas the flutterometer turns out not to converge to the true flutter speed during envelope expansion, due to inherent conservative predictions.

Algorithms achieving the *on-line in-flight* exploitation of flight test data are expected to allow a more direct exploration of the flight domain, with improved confidence and reduced costs. Among other challenges, one important issue to be addressed on-line is the flight flutter monitoring problem, stated as the problem of monitoring some specific damping coefficients. On the other hand, it is known, e.g. from Cramer-Rao bounds [122], that damping factors are difficult to estimate accurately. For improving the estimation of damping factors, and moreover for achieving this in real-time during flight tests, one possible although unexpected route is to rely on detection algorithms able to decide whether some damping factor decreases below some critical value or not. The rationale is that detection algorithms usually have a much shorter response time than identification algorithms.

Based on the residual (19), we have recently proposed [20] an on-line flutter monitoring test, which involves a temporal data-driven computation for the residual, and builds on a different asymptotic for the residual, combined with the on-line cumulative sum (Cusum) test of common use in quality control.

At a collaborative research level, we have been contributing to the establishment and coordination of a major cooperation within the Eurêka framework, devoted to improving the exploitation of flight test data, under natural excitation conditions (e.g. turbulence), enabling more direct exploration of the flight domain, with improved confidence and at reduced cost, see section 7.2.2.

5 Software

With the help of Yann Veillard and then Auguste Sam, engineers, Laurent Mevel and Maurice Goursat have developed a Scilab toolbox `http://www.irisa.fr/sigma2/constructif/modal.htm` devoted to modal analysis and vibration monitoring of structures or machines subjected to known or ambient (unknown) excitation [73, 76, 79, 75].

This toolbox performs the following tasks :

- *Output-only (*o-o*) subspace-based identification*, working batch-wise (sections 3.4 and 7.2.2). The problem is to identify the eigenstructure (eigenvalues and observed components of the

associated eigenvectors) of the state transition matrix of a linear dynamical system, using only the observation of some measured outputs summarized into a sequence of covariance matrices corresponding to successive time shifts. An overview of this method can be found in [6].

- *Input-output (I/O) subspace-based identification*, working batch-wise (sections 3.4 and 7.2.2). The problem is again to identify the eigenstructure, but now using the observation of some measured inputs and outputs summarized into a sequence of cross-covariance matrices. This method is described in [21, 55].

- *Automatic subspace-based modal analysis*, a pre-tuned version of the O-O and I/O identification methods above. This is described in [73, 79].

- *Automatic recursive subspace-based modal analysis*, a point-wise version of the O-O and I/O identification algorithms above. For this method, see [52].

- *Subspace-based identification through moving sensors data fusion* (section 3.4). The problem is to identify the eigenstructure based on a joint processing of signals registered at different time periods, and under different excitations. The key principles are described in [19] and a consistency result can be found in [22].

- *Damage detection*, working batch-wise (sections 3.2 and 3.4). Based on vibrations measurements processing, the problem is to perform early detection of small deviations of the structure w.r.t. a reference behavior considered as normal. Such an early detection of small deviations is mandatory for fatigue prevention. The algorithm confronts a new data record, summarized by covariance matrices, to a reference modal signature. The method is described in [4], and various application examples can be found in [5, 36, 61, 26, 24, 25, 11, 28].

- *Damage monitoring*, a point-wise version of the damage detection algorithm above. This is described in [25].

- *Modal diagnosis* (sections 3.3.1 and 3.4). This algorithm finds the modes the most affected by the detected deviation. For this method, see the articles [10, 7].

- *Damage localization* (sections 3.3.2 and 3.4). The problem is to find the part of the structure, and the associated structural parameters (e.g. masses, stiffness coefficients), which have been affected by the damage. We state and solve this problem as a detection, and not an (ill-posed) inverse estimation problem. This is explained in [25, 5, 66, 10].

- *Optimal sensor positioning for monitoring.* At the design stage of the monitoring system, a criterion is computed, which quantifies the relevance of a given sensor number and positioning for the purpose of structural health monitoring. For this criterion, see the articles [8, 5, 46].

This software (COSMAD 3.1.1) has been registered at the APP under the number

IDDN.FR.001.210011.000.S.A.2003.000.20700.

The modules have been tested by different partners, especially the French industrial partners, EADS and Dassault, within the FLITE project, section 7.2.2, and bilateral contracts, section 7.1.2. Based on intensive internal evaluation of the toolbox, EADS and CNES are currently investigating how to use the toolbox for the exploitation of the next Ariane 5 flight data sets.

This Scilab toolbox will continue to play the role of a programming and development environment for all our newly designed algorithms. Moreover, offering a *maintained* Scilab platform turns out to be a crucial factor in convincing industrial partners to undergo joint investigations with us, or to involve us within parternships in FP6 integrated projects proposals (see section 7.2.5).

6 Research program

The core of our research program is devoted to :

- The incorporation of additional model-based knowledge about the physics of the phenomenons involved in/over/below/around the structures to be monitored (thermodynamics, aerodynamics);
- The design of damage detection and localization algorithms based on these enriched models;
- The investigation of the cost of this increasing model complexity in terms of computational complexity, efficiency and robustness of the resulting new monitoring algorithms.

Moreover, with the goal of better diffusion and transfer of our approach, we plan to put some focus on more traditional mechanical engineering approaches (e.g. input/output, frequency domain) and to design detection algorithms associated with identification algorithms of those kinds.

Consequently, our research program contains :

- Design of variants of existing algorithms;
- Design of new detection algorithms, associated either with the new I/O identification algorithms discussed in [21] or with the recent polyreference LSCF frequency domain identification technique [137].
- Design of new algorithms, incorporating additional model-based knowledge about the physics of the phenomenons involved in/over/below/around the structures to be monitored (thermodynamics, aerodynamics);
- Performance analysis of both recently designed and incoming algorithms;
- In-depth experimentation and tuning.

Moreover, the toolbox will be enriched with additional computational and/or graphical facilities.

6.1 Modeling and parameterizations issues

As explained in section 3.4, one of the key tools in our vibration monitoring algorithms is the factorization (13), which directly results from the state-space model (8). An important feature of model (8) is that it is linear in the state X, linear in the parameterization (H, F) which is unfortunately *not* a parameterization to be used, but nonlinear in the *canonical* parameter θ defined in (9)-(10).

6.1.1 Models : from (mostly) linear to nonlinear

Model (8) results from the assumption that the structure's behavior is described by a continuous time stationary linear system :

$$M\ddot{\mathcal{Z}}(t) + C\dot{\mathcal{Z}}(t) + K\mathcal{Z}(t) = \varepsilon(t) \ , \quad Y(t) = L\mathcal{Z}(t) \tag{20}$$

where M, C, K are the mass, damping and stiffness matrices respectively, (high dimensional) vector $\mathcal{Z}$ collects the displacements of the degrees of freedom of the structure; measurements are collected in the (often, low dimensional) vector Y, and matrix L indicates which components of the state vector are actually measured (where the sensors are located). From the beginning of our investigations on this topic, we have been assuming that the external (non measured) force ε is modeled as a non-stationary white noise with time-varying covariance matrix $Q_\varepsilon(t)$. This is of course a rough approximation, originally due to the lack of consensus on the functional form and the actual fatigue effect of the fluid/structure interaction $\varepsilon(t, X)$ (seen as a feedback) for offshore platforms. Moreover, it has been recognized that the more complex a process model is, the more difficult its *robust* monitoring is. Hence the simple non-stationary white noise assumption for ε in (20). This assumption has turned out to be very efficient, from both points of view of actual experimental results obtained on many different structures, *and* theoretical consistency and robustness results obtained for both the identification and detection algorithms.

Now the situation has changed, from both theoretical and computational points of view. Advances in the physics (thermodynamics for civil engineering structures, aerodynamics for aircrafts) on the one hand, and on the power of embeddable computers of potential use for monitoring, result in a possible renewal for the design of monitoring algorithms. The idea is to complexify the model in (20), either for the purpose of rejection of the temperature effect seen as a nuisance (w.r.t. the monitoring objective), or for a better modeling of the interaction between the structural dynamics and the aerodynamics for monitoring the flutter phenomenon.

From a data information processing point of view, the challenge is very interesting indeed. Because it is impossible to know *a priori* whether the monitoring algorithms which will result from these more complex models, will *a posteriori* better solve the tradeoff efficiency/cost/robustness.

6.1.2 Parameterizations

The choice of models, parameterizations and criteria for monitoring is of crucial importance.

It is both natural for modeling and relevant for monitoring to select a parameterization in terms of physically meaningful parameters for characterizing involved elements and events. However, from a statistical inference point of view, some parameterizations resulting from appropriate transformations of the physical parameters may turn out to be more relevant, for identifiability reasons for example. On the other hand, the numerical behavior of the algorithms, in particular at the level of the various sensitivities – remember (7) – may lead to re-consider an initial choice of parameterization. The single question : is a geometric parameterization, underlying a finite elements model updating method, useful, if not optimal, for the damage localization method in 3.3.2 [10], is still open.

6.2 Algorithms : design and performance analysis

In our mind, damage *detection*, seen as a model to data approach as described above, should be pushed as an original alternative to a more classical approach based on *identification* procedures.

Nonetheless, it has appeared that, in parallel to pushing forward damage detection methods, substantial work has to be done on the identification front for at least three reasons :

- From a practical pragmatic point of view, one cannot hope pushing forward some original damage detection techniques without showing any ongoing activity in identification.
- Damage detection can also be performed using repeated identification, as most of the community do. Thus such an activity must be pursued.
- Damage detection algorithms are often designed on the basis of some identification procedure. Thus keeping well aware of the identification scene can be a source of inspiration for new detection algorithms.
- Comparison has to be done between our in house identification techniques and some old and new identification techniques developed in the field. Thus implementing those techniques is a time consuming but profitable task.

6.2.1 Identification

The following tasks are planned within the identification field.

Handling the model order. Many identification methods are based on a multiple order approach. This includes popular data driven methods such as subspace identification, or frequency domain methods, such as the LSCF (Least Squares Complex Frequency) method. Practically, such methods are run on the construction of a stabilization diagram, which plots the evolution of the identified frequencies (modes) w.r.t. the model order. Empirically, it has been shown that true modes tend to stabilize with increasing model order, whereas mathematical modes tends to be unstable. Lots of efforts have been devoted to, first, automatically exploit those stabilization diagrams, and, second, to obtain diagrams as clean as possible. Some modifications of the subspace methods will be considered in order to obtain such results.

Handling frequency domain data. Up to now, the core of the team's identification approaches is based on working directly with time domain data, by computing cross correlations (subspace-based method in 3.4), prediction errors (least square), or maximum likelihood estimates. We have been recently [21] and will be considering another approach working with frequency domain data, e.g. methods such as Polymax, LSCF and LSCE, for two main reasons. First, we must compare our methods (such as those available in the COSMAD toolbox) to those very popular methods within the mechanical community. Second, they are good candidates for being the core of some new model to data detection techniques. This is especially the case of a technique like Polymax, due to its capability to yield clean stabilization diagrams. Methods such as those in [140] might also be of interest.

Recursive subspace identification. An ongoing work with KUL [52] is to derive both recursive versions of the subspace methods and fast procedure for the automated extraction of the estimates from the stabilization diagram in order to obtain a realistic near real time monitoring identification procedure and circumvent the main practical drawback of identification monitoring.

Incorporating the likelihood function. The Maximum Likelihood Estimation (MLE) approach is now being considered as a new topic for the identification of mechanical structures. Maximizing the likelihood is usually avoided for real structures identification, because of lack of robustness with respect to real data and high dependency on initial condition. Our approach builds on the expertise of Laurent Mevel in the study of the maximum likelihood for hidden Markov models [23], and targets to build a MLE approach, seen as a post-processing step to subspace identification (or conversely using subspace as an initial condition), and robust to non stationarities. This could also be useful to derive confidence intervals for estimates, something which subspace-based estimates lack providing.

Using particle filters estimates. As a follow up to a previous joint work with F. Legland and F. Campillo, particle methods are investigated for real time tracking of the modal characteristics of the monitored structure. Recursive estimates are defined, which are based on the computation of both the law of the linear system state with respect to the observations, and some of its derivatives with respect to the tracked parameters. Such estimation methods were studied in the Ph.D. Thesis of Laurent Mevel for the HMM case. Application to mechanical structures and to the use of interacting particles systems are the main new challenges of this work. A preliminary attempt is reported in [90].

6.2.2 Damage detection

The following tasks are planned within the detection field.

Detection algorithms associated with other estimating functions. As explained in section 3.2, our detection approach is a very general one. Apart from mechanical structures, it has been applied by the team members in many areas, including HMM [62]. Different estimating functions have been used for this purpose [14], such as the (likelihood) score, the LS-score (gradient of the squared prediction error), or the (IV-based) instrumental statistics [98, 7]. The versatility of the method calls for its application with different (including nonlinear) models, and its extension to handle other estimating functions.

We plan to design new damage detection algorithms, associated either with the new I/O identification algorithms discussed in [21] or with the recent polyreference LSCF frequency domain identification technique [137], a widely accepted and used approach in the field of mechanical engineering.

A preliminary investigation of frequency domain local tests has been described in [50].

Detection algorithms as a post-processing from some identification techniques. When performing identification, even considering that all problems are solved, i.e. we got an on-line automated monitoring procedure, it is not always clear whether the estimates are statistically different from each other, or if we only got variability due to large (possibly unknown) confidence intervals. One possibility to circumvent this would be to confront the result of the identification with the reference model through some appropriate function, e.g. perform some damage detection scheme as described above. A first example is the currently investigated particle systems identification (see 6.2.1). Confronting different estimation results for the state transition matrix by using a χ^2-test could yield some warning without relying on the computationally expensive and prone-to-statistical-error eigenvalues resolution.

Incorporating and testing thermodynamics. The Ph.D. thesis of Houssein Nasser is devoted to the rejection of the temperature effect, seen as a nuisance parameter, for vibration monitoring of civil engineering structures. Regarding the temperature effect, this work is done in collaboration with D. Chapelle (MACS project), within the framework of the CONSTRUCTIF project (see 7.1.1). Within this framework, we will have access to data recorded in a heat chamber available at LCPC, and thus we should have the opportunity to test the relevance of the (reduced) models of the temperature effect that will be elaborated. Regarding nuisance elimination or rejection, several techniques can be considered [12] and compared.

Incorporating and testing aerodynamics. In the framework of FliTE (see 7.2.2), a simulation program, based on a ground vibration test of a commercial airplane, has been available for us by the VUB partners. This program simulates a time-invariant airplane, excited by one force at the left wing and by spatially correlated noise (ambient turbulent forces). In the course of a student project, this simulator is to be evaluated this spring, and our new flutter test [20, 70] experimented.

We are in the process of establishing a collaboration with Jonathan Cooper, from the Dynamics and Aero-Elasticity Research Group at University of Manchester (UK), for investigating the issue of aerodynamics and structural dynamics interaction. J. Cooper has been a member of the NATO RTO (AGARD) working groups on "Design of Future Aircraft for Loads" and "Qualification using Analysis" (see 7.2.3).

An aircraft aero-elastic model, together with its state-space form, is available in [127], together with rational functions capturing the effect of unsteady aerodynamics. This model is restricted to capture flutter phenomena based on linear effects.

A contact has been recently established with Boeing Commercial Airplanes, Seattle, and a formal request has been formulated for having access to real flutter model data registered during wind tunnel tests. These data will be very useful for assessing the capabilities of our identification and flutter detection algorithms [20, 70].

6.2.3 Damage diagnostics and localization

Improving Jacobian computations. An ongoing investigation within the CONSTRUCTIF project (see 7.1.1) is to evaluate and improve the current computation of the sensitivities of the modal parameters with respect to the Finite Element model. Currently, the computation is based on a rather rough derivation of the fundamental law of the mechanics [94, 10]. Different new approaches will be envisaged. The computational cost together with the quality of the sensitivities will be taken into account.

Revisiting the interplay between Jacobian computation and aggregation. As seen above, our statistical approach is based on the construction of a residual vector built from data collected on the structure in-operation and from a reference model, namely a collection of parameters and functions (sensitivities, covariance matrix) calculated beforehand on the healthy structure. The χ^2-test in (4) gives an alarm when the new data significantly (in a statistical sense) differ from the reference model.

The χ^2-test involves a Jacobian collecting the sensitivities of the residual with respect to the parameters of interest. In the case of a simple monitoring, whose goal is only to know if a damage

has occurred or not, the number of parameters is relatively low, and the Jacobean likely to be full rank. Then, provided that the residual is well calculated, the computation of the quadratic form in (7) is not degenerated. When a large number of parameters is involved, which is the case for damage localization on finite elements structures, the number of finite elements (typically several thousands) is much higher than the number (a hundred) of statistical parameters which govern the residual. In such a case, the number of unknown factors – for example the variations in the masses and stiffness coefficients of each finite element – to be recovered for performing damage localization, becomes too high. An immediate consequence is that the safe and damaged states of some of the elements can no longer be distinguished from a statistical point of view using (7). If two elements have this property of non separability, then a reaction of the test statistics implies that at least one of them is damaged. We call *macro-damage* a set (a class) of elements having this property. For the same macro class, it is useless to perform the monitoring on more than one representative of the class. It is thus interesting to know in advance the distribution of these classes in the structure. It is also important to study the modification of a class spreading due to a variation in the sensor positioning. Actually, various sensors sets do not have the same separability properties, and thus do not provide the same classes.

For overcoming this issue, we plan to investigate two approaches :

- A statistical approach, based on the calculation of the Jacobian of the residual, predicting that if two columns of the Jacobian are close for a certain metric taking into account the uncertainties, then the parameters will be non separable. This is the method described above. This implies to calculate the Jacobian for all the elements, and then to reduce the problem dimension by classification techniques.

- What we want to investigate is the benefit that our damage localization technique could get from using FEM-based clustering approaches, such as the so called *sub-structuring* method. Such a method first reduces the model, based on finite elements model updating techniques, and then computes the Jacobian on the reduced structure.

These two approaches must be evaluated from two points of view: the algorithmic cost to obtain the classes, and the advantages and drawbacks of the two resulting sets of macro-damages. It might also be interesting to design and develop a mixed approach combining the best properties of the two methods.

This is the topic of the post-doc subject we have proposed.

Criteria for model updating. Some research efforts could be put on the choice of improved criteria (objective functions to be optimized) for the purpose of FEM updating. Most updating methods handle a 'distance' between two sets of 'measured' and 'calculated' frequencies, but none of the criteria seems to be an actual spectral distance measure, which is somewhat puzzling. Moreover, as for damage detection/damage localization, updating a FEM from measurements might not necessarily require first estimating the modes from those measurements.

On the other hand, all the experimentations based on the residual (2) suggest that it really plays the role of a good parameterized summary of the data, if not of a sufficient statistics. How to handle this residual within a FEM updating procedure is a topic which is to be investigated with some of the partners of the ACI SI project in section 7.1.1.

6.2.4 Optimal sensor positioning and damage detectability

Optimal sensor positioning. Determining the best number and positions of sensors to be used for SHM is of crucial importance for costs and efficiency reasons. More generally, the issue of sensor positioning for investigating the properties of dynamical systems has been investigated from different points of view: average energy, observability, controllability, monitoring performance index (e.g. power of statistical tests), entropy, information content of measured or transformed data.

Different types of criteria have been used for quantifying the relevance of the number and the positions of sensors in a given set, and they have been optimized for selecting the best possible sets. In particular, several scalar functions of matrices such as observability and controllability matrices, Fisher information matrix, modal assurance criterion matrix, have been proposed. When optimizing the performances of damage detection algorithms, one crucial issue, for comparing two sensors sets, is to compensate somehow for different numbers of degrees of freedom resulting from different numbers of sensors.

Our purpose is to better understand the relationships between these different types of criteria, and discuss their relevance for structural health monitoring, from both points of view of damage detection and damage localization, and to evaluate on relevant examples the criterion we proposed earlier [8, 94]. This work is part of the work program of the CONSTRUCTIF project in 7.1.1.

Damage detectability. This issue is also to be investigated within the CONSTRUCTIF project in 7.1.1. The *a priori* analytical and numerical investigation of damage detectability and diagnosticability is of course highly useful in practice. Such an investigation is a complement of a detailed analysis of experimental results concerning the actual capabilities of the proposed damage detection and localization algorithms. Different points of view and methods can be used for this purpose : damage *observability*, damage *controllability*, *information* contained in the data about the damages, *distance* between the damage-free and the damaged systems, signature of the damage on residuals, *power* of the damage detection algorithms [16].

A deeper understanding of the relationships between those different criteria, and a wider numerical investigation, are our main expected achievements on that issue.

7 Grants and collaborations

7.1 National projects

7.1.1 ACI SI CONSTRUCTIF

Laurent Mevel is coordinator of the a project entitled *COuplage de coNcepts pour la Surveillance de sTRUCTures mécaniques InFormatisées*, project labeled in 2003 by the national program for computer and security (ACI Sécurité & Informatique).

Our partners are MSSMat (Laboratoire de Mécanique des Sols, Structures et Matériaux, École Centrale de Paris and CNRS), Laboratoire Central des Ponts et Chaussées (Service Métrologie et Instrumentation), and the INRIA project MACS (Rocquencourt).

The objectives of the project are, on the one hand, the intrinsic coupling of statistical models of sensor data with fine models of the physical phenomenons governing the instrumented structures, and, on the other hand, the mixing of statistical inference, data assimilation, finite element model updating and optimization methods for structural dynamics. The investigation of potential mutual benefits of criteria used for different purposes by various methods designed in different scientific communities, is the central axis of the project. The main object of the study is the intrinsic involvement of the temperature effect, which is a generic issue for vibration monitoring of civil engineering structures.

7.1.2 EADS grants

Two contracts, under the responsibility of Maurice Goursat, with EADS Launch Vehicles Systems in 2002 and EADS Space Transportation (December 2002 - june 2003), respectively, have been devoted to the *Modal analysis of a launch vehicle*, during which we have processed Ariane 5 flight data sets.

The objective was to provide a methodology for off-line/online monitoring of vibration modes of a launcher in launch situation. The project is a follow-up of a previous contract, where rough evaluations of the launcher data sets were conducted. In this project, we went deeply into analyzing those datasets using input and feedback from the industrial partner, who provided datasets, end results requirements and comments. The intended result was to obtain both a fully automated identification procedure and to evaluate the influence of the tuning parameters on the identification results. The objective was then to hide as much as possible unnecessary parameters and to explain as much as possible the important and required tuning buttons.

This contract has thus provided us with another opportunity for improving, tuning and testing our techniques through our modal toolbox. A massive rewriting of our online monitoring toolbox has been performed, both for the features and in the graphical user interface [79, 75, 81, 77]; see section 5.

The outcome of these contracts for both partners has been very positive [149]. A new collaboration should be established within the next few months.

7.2 European projects

In this section, we present an overview of recent, current or future (if accepted) European projects, which we have been/are/will be involved in.

7.2.1 Eurêka project SINOPSYS (1996-1999)

The object of Eurêka project no 1562 Sinopsys (Model Based **S**tructural Monitoring Using **IN-OP**eration **SYS**tem Identification) coordinated by Lms (Leuven Measurements Systems, Leuven, Belgique) has been to develop and integrate modal analysis and vibration monitoring algorithms devoted to the processing of data recorded in-operation, namely during the actual functioning of the considered structure or machine, without artificial excitation, speeding down or stopping. The present team members have been involved within Sinopsys.

Our main contribution to Sinopsys has been an original set of algorithms for multi-sensor signal processing (e.g. accelerometer measurements) that produces intelligent warnings, namely warnings that reveal the hidden causes of the defects or damage undergone by the machine or structure. This software can be embedded and work online. Among the actual data that Inria had to process with this software is the Ariane 5 test flight data.

During the first stage of the Sinopsys project, focussed on modal analysis, we have improved our interactive mode selection and validation procedures, and developed a module for model validation, performing a crossed validation of an identification result on a validation data set. Within a second stage, we have developed a fatigue detection tool, which evaluates for each mode the extent of the modification in the modal behavior. This works on laboratory data sets involving a measured excitation, as well as on in-situ data without measuring the excitation. A third stage has been devoted to the development of a fatigue diagnostics tool, where the fatigues or damages are explained in terms of modifications in volumic mass or Young modulus, with a localization of the changes on the structure.

During and after SINOPSYS, the entire set of tools has been integrated within the LMS CADA_X system on the one hand, and within the MODAL/COSMAD toolbox for the SCILAB free-ware on the other hand; see section 5.

7.2.2 Eurêka project FliTE (2000-2004) and proposal FliTE2 (2005 ?)

The Eurêka project no 2419 FliTE (**Fli**ght **T**est **E**asy) falls within the aeronautical domain, and has been initiated after some successful preliminary experiments with our output-only identification algorithms on flight data [38, 3]. The project is coordinated by the industrial test laboratory Sopemea (France). The partners are Dassault–Aviation and EADS (AeroMatra Airbus) (France), LMS , KUL and VUB (Belgium), Cracow university and the company PZL–Mielec (Poland), and INRIA (the present team members).

The FliTE project aims at a better exploitation of flight test data, exploiting data recorded under natural excitation conditions (e.g., turbulent), without resorting to artificial control surface excitation and other types of excitation inputs. A second objective of FliTE is an improvement of the flight test procedures themselves. One of the intended application examples is the A3XX.

Our expertise in output-only system identification methods, for modal analysis of vibrating structures under ambient and non-stationary excitation, and thus under unknown inputs, is central in the project [6, 19, 22]. The team members are responsible for the task *development of algorithms and associated methods*, and for the corresponding task reports. Moreover, Albert Benveniste helps Sopemea in the scientific coordination of the project.

The achievements of this project belong to several frameworks, conceptual investigations, experimental results and software developments.

On the conceptual side, three investigations have been conducted, on recursive subspace algorithms [52], particular filtering algorithms [90], and on flutter monitoring algorithms [64, 70, 20], respectively. The work on recursive subspace algorithms has been the topic of the visit of Ivan Goethals (KUL/SISTA), see section 8.5.

The flutter monitoring problem has been addressed as the problem of monitoring a damping coefficient, and a first theoretical solution has been investigated. The idea is to use the same subspace-based residual as we use for structural health monitoring, and to design a unilateral test statistics for detecting that a given damping coefficient decreases towards zero. Since this problem is no longer a local hypotheses testing problem, we have used another asymptotic approximation for the residual (different from the local approximation in section 3.2), and a cumulative sum test built on the residual. This algorithm works on-line [64, 70, 20].

From an experimental point of view, this project has provided lots of opportunities for testing and improving our identification and detection techniques. On the identification front, large aircraft datasets have been successfully investigated using our online identification monitoring toolbox, for both full and recursive subspace algorithms. On the detection side, massive progress have been achieved in flutter monitoring using our new detection scheme. It allows us to successfully track damping values (the only really fluctuating part of the modes) without re-identifying the modes. This feature speeds up the process tremendously. Notice that both identification techniques and detection techniques have been tested on the same aircraft dataset and gave results cross-validating the methods.

On the software side, the development of the MODAL/COSMAD toolbox to be used with SCILAB has been pursued, the above recursive identification algorithms and the flutter monitoring algorithms incorporated, see section 5.

In FliTE, the basis for novel techniques for in-flight test data structural analysis was developed, involving both controlled and uncontrolled (natural) excitations. Since the results of FliTE have been positively evaluated, the partners have agreed with the national funding agencies to submit a follow-up project, FliTE2, which partnership is extended to ONERA/CERT. A presentation to the French Eurêka secretariat should take place by the end of April. FliTE2 will expand the results of FliTE to improve the methods, algorithms, and software. Whereas the main focus of FliTE has been on identification, in FliTE2 a strong emphasis will be put on fast detection algorithms, in particular for the flutter monitoring problem.

7.2.3 Marie Curie RTN proposal FliTE-Net

A Marie Curie RTN proposal called FliTE-Net (*Flight Test Easy: Accompanying Training Actions*), under the coordination of Michèle Basseville, has been submitted upon the November 2003 call.

In the context sketched in sections 4.3 and 6.2.2, FliTE-Net is intended to develop new flight test data exploitation methods for structural and flutter analysis. The consortium collects skills from aeronautics, mechanical, and control engineering disciplines. In addition to the academic partners, it involves leading partners from aircraft industry and high-tech engineering companies.

FliTE-Net is an accompanying measure to the Eurêka FliTE2 project, which is to be submitted in 2004 as a follow-up of the Eurêka FliTE project No 2419 to be completed soon. FliTE-Net will complement FliTE2, providing the necessary tutorial, course-ware, and summer school material, in order to sustain the transfer of FliTE2 results to industry at large. FliTE-Net will also perform complementary exploratory research investigation and prepare the consortium for future advances. FliTE-Net extends the partnership of FliTE and FliTE2 by including the Dynamics and Aero-Elasticity Research Group (U. Manchester, UK), a world leader in flutter analysis.

7.2.4 FP5 Growth Thematic Network SAMCO (2002-2005)

The thematic network *Structural Assessment Monitoring and Control* has been launched in October 2001 within the framework of the Growth program. It aims at becoming a focal point of reference in the field of assessment, monitoring and control of civil and industrial structures, in particular the transportation infrastructure (bridges, ...).

Several partners of the network have proposed our participation, and in February 2002 we became a participating member, especially involved in the thematic group *Monitoring and Assessment*. This turns out to be a useful complement to the diffusion of our knowledge and expertise in vibration monitoring, as was the case during our participation to the former COST F3 *Structural Dynamics* (see 7.2.7).

7.2.5 FP6 NMP proposals

Within the SAMCO network, we have been involved in the E-MOI (**E**uropean **M**onitoring **I**nitiative) IP proposal submitted in March 2003 within the FP6 NMP framework. We have offered SCILAB as an open platform for the integration of the modules for algorithms and methods covering the objectives of automatic modal analysis, automatic modal and statistical damage detection methods. We have also offered the SCILAB modal analysis and monitoring toolbox, see section 5.

Three IP proposals issued from a split and thorough revision of the E-MOI proposal have been submitted on March 2, 2004 upon the second FP6 NMP call : METRON, E-MASS, SALMAPS. The hearing of the proposals accepted in stage 2 should take place at the end of April. The core group

of partners qualified for monitoring is basically the same within all the consortia. The competition among the academic partners of SAMCO for being involved in this group has been quite sharp. We have been asked to be involved therein, if not to lead an axis, based on our expertise on identification, change detection and vibration monitoring, and with the same SCILAB-based offer as above.

7.2.6 Marie Curie RTN proposal ERNSI

The team members have participated to the EU TMR Project *System Identification* (SI) (2000-2003), and to the former RTN *European Research Network System Identification* (ERNSI) (1992-1999). They are involved in the Marie Curie RTN proposal ERNSI submitted upon the November 2003 call.

7.2.7 COST F3 Structural Dynamics (1999-2001)

Michèle Basseville has been a member of the *Health monitoring and damage detection* working group WG2 of the COST F3, and has also attended the meetings of the *Finite element model updating methods* group WG1.

We have participated to the benchmark activity of WG2 [24, 25].

8 Positioning and partnership

The SISTHEM project proposal combines statistical inference techniques for system identification, detection and diagnosis, applied to structural health monitoring. Few groups, worldwide, combine these characteristics together.

8.1 Local positioning

8.1.1 Within IRISA

We share with the VISTA project the motivation for and the research on designing multiple sensors information data processing algorithms, based on both models of the underlying physical phenomenons and statistical inference techniques.

The ASPI research team is designing and analyzing particle filtering methods for statistical inference in HMM. As mentioned in section 6.2.1, we plan to investigate further the potential benefit of the application of such techniques to our problems.

8.1.2 Within/w.r.t. academic partners

Up to our knowledge, none of the teams performing research in mechanics on the Rennes 1/Beaulieu campus is involved in sensor-based SHM investigations.

The research themes within the LARMAUR – LAboratoire de Recherche en Mécanique Appliquée de l'Université de Rennes 1 – concentrate on physical and chemical rupture mechanisms for fragile materials, formatting procedures for such materials, and control of steel surface processing techniques.

The Mécanique team at the Mathematics Research Institute (IRMAR) investigates the modelling and numerical simulation of mechanical and biomechanical systems, turbulences and other geophysical fluid phenomenons, and oceanography.

The Groupe de Recherche en Génie Civil (GRGC) at INSA performs research ranging from experimental behavior of materials and structures to numerical methods for structural computation (nonlinear FEM) and analysis.

The laboratoire de Mécanique Appliquée, Automatique et Géomécanique (MA2G) also at INSA investigates mechanical processes involved in various solid materials formatting operations.

8.2 Within France

8.2.1 Within INRIA

The SISTHEM project proposal is expected within the research theme *Systèmes Numériques,* research programme *Données déterministes et stochastiques, observation et optimisation.* The team within this programme that is closest in style is Idopt in Grenoble, headed by François-Xavier Le Dimet. Regarding the statistical tools used, links to the Select project team headed by Gilles Celeux can be mentioned.

However, our main collaborations are with other teams. Due to the participation of Maurice Goursat, head of team METALAU in Rocquencourt, as well as the central role of the COSMAD toolbox for SCILAB, special ties with METALAU need to be mentioned.

For its research, SISTHEM will tightly combine models from structural dynamics, aerodynamics, etc, together with techniques from mathematical statistics. Lacking expertise in the former area, SISTHEM has to rely on close partnerships with other teams for the application domains of structural dynamics, aerodynamics, etc. The MACS project at Rocquencourt, headed by Dominique Chapelle, is therefore a key partner of SISTHEM. This team participates to the CONSTRUCTIF ACI SI joint research project in the area of civil engineering.

Links with other teams of INRIA are milder. We should, however, mention the Sosso team at Rocquencourt, headed by Michel Sorine. Due to his nearly universal knowledge and competence in the modeling of physical phenomena, Michel has assisted us in the past several times, for various applications. This may also occur in the future.

8.2.2 Within CNRS

The design of signal processing methods for mechanical engineering applications (mainly rotating machines) is investigated in the Laboratoire Roberval at Université de Technologie de Compiègne (Menad Sidahmed, Jérôme Antoni), and in the Laboratoire des Images et Signaux (LIS) at INPG (Nadine Martin, Christine Servière).

Up to our knowledge, no team in France has a profile similar to ours, in the combined use of statistical processing and system identification for structural dynamics. Therefore, the discussion is enlarged to the two communities of statistical signal processing and system identification on the one hand, and structural dynamics on the other hand.

Statistical signal processing and system identification. This community is the background community of SISTHEM. It can be approximately identified with the GDR ISIS, joint research group supported by CNRS where Michèle Basseville has had responsibilities for a long period of time, and the Réseau Thématique Pluridisciplinaire RTP24 *Mathématiques de l'Information et des Systèmes.*

The closest links are with the teams of Igor Nikiforov at Université Technologique de Troyes, Laboratoire de Modélisation et Sûreté des Systèmes (LM2S), and Éric Moulines at Telecom Paris, Laboratoire de Traitement et de Communication de l'Information (LTCI).

Michèle Basseville and Igor Nikiforov co-authored the book [1] on change detection in signals and dynamical systems. Their cooperation has contributed to the development of the so-called *local approach to change detection and diagnosis,* an enhancement of the original approach by Le Cam [110], that is now the central statistical background of SISTHEM. Igor Nikiforov, however, does not investigate mechanical engineering applications, and has a lower expertise on monitoring dynamical systems than we have.

SISTHEM shares with the TSAC group at LTCI (in particular, Éric Moulines and Jean-François Cardoso) the objective of and scientific background for designing advanced statistical multiple signal processing algorithms.

Structural dynamics. The structural dynamics community has become a partner of the SISTHEM members only recently, in particular *via* the ACI SI CONSTRUCTIF project (see 7.1.1) and the preparation of the FliTE2 proposal (see 7.2.2), and not so much before year 2000.

Étienne Balmès from MSSMat (Laboratoire de Mécanique des Sols, Structures et Matériaux, École Centrale de Paris and CNRS) participates to the CONSTRUCTIF project. Among other questions, our collaboration deals with the Jacobian computations discussed in 6.2.3.

In the past, we have had contacts with René Bouc (LMA Marseille) and Gérard Lallement (LMA Besançon), for the Ph.D. committees [95, 94], respectively, and with Pierre Ladevèze (LMT Cachan).

Highly fruitful discussions with two members of LMT Cachan, unfortunately no longer in that lab., have been conducted within the framework of the COST F3 (see 7.2.7). The Structures & Systems Division at LMT (headed by Pierre Ladevèze) is certainly a lab. we should soon get into contact with.

Monitoring and supervision. The S3 cooperative research group, established by Marcel Staroswiecki (LAIL), and currently headed by Didier Maquin (CRAN), Christophe Bérenguer (LM2S), and Qinghua Zhang (IRISA), collects teams mainly from control, with the support of the RTP 20 headed by Sylviane Gentil (LAG). The Imalaya research group, headed by Louise Travé (LAAS), collects teams from control and artificial intelligence. The Dream team at IRISA, headed by Marie-Odile Cordier, participates to Imalaya. The S3 group focuses on monitoring and diagnosis of dynamical systems. However, the involved teams put a greater emphasis on monitoring sensors and actuators systems, than on monitoring the dynamics of the plant or structure itself – although one must admit that the boundary between these different aspects is somewhat fuzzy.

8.2.3 Other

Frédéric Bourquin, from LCPC - Laboratoire Central des Ponts et Chaussées (Service Métrologie et Instrumentation), and also collaborator of MACS, participates to the CONSTRUCTIF project. One important contribution of LCPC to this project, among others, is to provide us with data recorded in a thermal chamber, for validating the models of the temperature effects.

During the course of FliTE, and the preparation of FliTE2, we have been in contact with Alain Bucharles from ONERA/CERT, System Control and Flight Dynamics department. This team is involved in the FliTE2 partnership.

We have attended the *Entretiens du Réseau de Génie Civil et Urbain* in 2002 and 2003, and the national workshop *Auscultation, diagnostic et évaluation des ouvrages* organized on request of the

Direction de la Recherche (DRAST) of the Ministère de l'Équipement (FNTP, Paris, November 25-26, 2003).

We should also mention the Miriad Technologies company, founded by Robert Azencott. Miriad Technologies focuses on *black-box* statistical techniques for industrial systems monitoring and diagnosis. We know each other, and we may tighten our relations in the future whenever needed.

8.3 Within Europe

The groups of Johan Schoukens (Fundamental Electricity and Instrumentation department - ELEC, identification team) and Patrick Guillaume (mechanical engineering department, acoustics and vibration group), at Vrije Universiteit Brussels (VUB), and the groups of Bart de Moor (Signals, Identification, System Theory and Automation - SISTA) and Guido de Roeck (civil engineering department) at Katholieke Universiteit Leuven (KUL), are important actors worldwide. They share a profile similar to that of SISTHEM. The Eurêka projects SINOPSYS and then FliTE collected these groups together with the members of SISTHEM. Since the beginning of the 80's, these groups provide the company LMS with researchers, engineers, and technologies. SISTHEM has close ties with LMS since 1996, particularly with Herman van der Auweraer, director for R&D.

In 1999, Rune Brincker [133] and Palle Andersen [150] from Aalborg University, Department of Building Technology and Structural Engineering, founded the Danish company *Structural Vibration Solutions ApS*. This startup develops the ARTeMIS product family, which focuses on output-only structural analysis, by using in particular (but not only) subspace-based techniques. These products are distributed in Denmark by the sensor company Brüel & Kjær, in Switzerlanb by GeoSIG, and also worlwide.

During the early stage of SINOPSYS, and during the preparation of FliTE-Net, we have been in contact with Jonathan Cooper, from the Dynamics and Aero-Elasticity Research Group at University of Manchester (UK), who is involved in the FliTE-Net proposal. He has been a member of the NATO RTO (AGARD) working groups on "Design of Future Aircraft for Loads" and "Qualification using Analysis". The collaboration with his team is of crucial importance to SISTHEM for the investigations planned in 6.2.2. Should the FliTE-Net proposal be rejected, we intend to submit a PAI project to make the collaboration feasible.

In the framework of SAMCO, we are in contact with Costas Papadimitriou from Thessaly University (GR), who has designed Fisher information-based criteria for optimal sensor positioning, very similar to ours.

In the framework of the former COST F3 (see 7.2.7), we have had numerous discussions with Michael Link from U. Kassel (FRG), Keith Worden from the SHM group in U. Sheffield (UK), Jean-Claude Golinval from U.Liège (B), Mike Friswell from Aeronautics Department in U. Bristol (UK), Spillios Fassois from U. Patras (GR).

Our main contacts within ERNSI (see 7.2.6) have been, and still are, Lennart Ljung and Fredrik Gustafsson from Linköping U. (S), Jan H. van Schuppen from CWI Research Group Control and System Theory in Amsterdam (NL), Giorgio Picci from Padova U. (I), Manfred Deistler and Dietmar Bauer from Vienna TU (A), Torsten Söderström from Uppsala U. (S), Bernard Hanzon from

Vrije Universiteit in Leiden (NL).

8.4 W.r.t. USA

Regarding the USA, one should say that they heavily dominate the topic. In average years, above 70% of the papers presented at the IMAC conference originate from the following list of institutions: NASA, Boeing, Los Alamos National labs, Sandia Labs and JPL, and the universities of Houston. However, with the exception of a few individuals (such as David Zimmerman from Houston, and James Beck from Caltech), statistical techniques are usually not so much used by these teams.

They benefit from huge computing equipment and key experimental platforms, including the various spacecrafts from the NASA. National labs behave both as research labs and as service providers, toward large companies involved in mechanical engineering. This has the surprising consequence that US SME's are not dominant worldwide in the market segment of services in structural dynamics – compare with the leadership of LMS. This is a chance for EU. Nevertheless, we have some scientific contacts with François Hemez and Charles Farrar from the SHM department at Los Alamos National Laboratory, and David Zimmerman at Houston University.

Michèle Basseville has presented our damage detection approach at the MIT Aeronautics and Astronautics Department (James Paduano and Éric Feron).

A visit to us of Fu-Kuo Chang from the Stanford U. Aeronautics and Astronautics Department is under discussion.

We have recently established a contact with Charles Pickrel (Boeing Commercial Airplanes), see 6.2.2.

8.5 Visits

Ivan Goethals, a PhD student of Bart De Moor at KUL / SISTA has visited us during two weeks in February 2003, in the framework and with the support of the FLITE project. We have jointly tried to speed up the output–only subspace–based identification algorithm by implementing recursive versions of the SVD [52].

Laurent Mevel and Ivan Goethals have been invited to submit a review paper on modal analysis under unobservable excitations, in a series of review papers that will be published to commemorate the 20th anniversary of the journal *Mechanical Systems and Signal Processing*.

9 Research animation and dissemination

9.1 National and international animation

Michèle Basseville is member of the :

- Board of the scientific committee of the Computer Security program launched by the French Ministry of Research (*ACI Sécurité & Informatique*),
- Leading committee of the CNRS Groupement de Recherche GDR ISIS (*Information, Signal, Images*),
- Steering committee of the CNRS Réseau Thématique Pluridisciplinaire RTP24 *Mathématiques de l'Information et des Systèmes*.

Laurent Mevel is responsible of the CONSTRUCTIF project, within the framework of the Computer Security program; see section 7.1.

Michèle Basseville has been or still is :

- Co-chair of the IFAC technical committee *Fault Detection, Supervision and Safety of Technical Processes*, within the coordinating committee *Industrial Applications*;
- Member of the technical committee *Modeling, Identification and Signal Processing*, within the coordinating committee *Systems and Signals*;
- Registered within the *Distinguished Lecturer Program* of the IEEE Control Systems Society for the period 2001-2004, with a general talk on monitoring and change detection, and another one to vibration monitoring. The corresponding material has been sollicitated for publication within the DLNET (Digital Library Network for Engineering and Technology) supported by NSF as a partner of the NSDL (National Science Digital Library);
- Invited to deliver :
  - The opening plenary talk at the IFAC triennial symposium Safeprocess'03 in Washington D.C. [45];
  - A tutorial talk at the IFAC triennial world conference b'02 in Barcelona, Spain [42];
  - One of the four plenary talks at the IFAC triennial symposium SYSID'97 in Kitakyushu, Japan [43].

9.2 Scientific information and evaluation

Michèle Basseville has been, still is or will be :

- Associate editor for the IFAC journal *Automatica*, in charge of the fault detection and identification topic, since 1992;
- Associate editor for the journal *Mechanical Systems and Signal Processing*, since 1995;
- Associate editor within the IEEE Control Systems Society Conference Editorial Board, since 2002, in charge of the evaluation of papers submitted to CDC-ECC'05, CDC'04, ACC'04, CDC'03, ACC'03, CDC'02;
- Member of the international program committees of Safeprocess'06, CIFA'04, ECC'03, SYSID'03, Safeprocess'03, F3'01, DAMAS'01, SYSID'00, Safeprocess'00, UKACC'98, Safeprocess'97, ECC'97;
- Co-guest editor, in charge of the scientific and material coordination, of :
  - A special issue of the *International Journal of Adaptive Control and Signal Processing*, entitled *Fault Detection and Isolation*, in collaboration with Thomas Parisini (Politecnico di Milano), Nov. 2000;
  - A special section of *Mechanical Systems and Signal Processing*, entitled *Model-based structural identification and monitoring using in-operation data*, in collaboration with Étienne Balmès (École Centrale Paris), Nov. 1999;

- Organizer of invited sessions : *Flite* at SYSID'03; *Advanced methods for fault detection and isolation* at SYSID'97.

She has been or still is sollicitated for the evaluation of Research Grant Projects submitted to the Swedish Research Council for Engineering Sciences, the Swedish Foundation for Strategic Research, the Programme for Strategic Technological Research' (GBOU) of the IWT (Institute for the Promotion of Innovation by Science and Technology in Flanders), and the Australian Research Council.

9.3 Teaching and training

The team members are involved in the Marie Curie RTN proposal called FliTE-Net (*Flight Test Easy: Accompanying Training Actions*), aimed at providing the necessary tutorial, course-ware, and summer school material, in order to sustain the transfer of FliTE2 results to industry at large; see section 7.2.3.

Michèle Basseville teaches *Statistical methods for in-situ monitoring* within the module *Tools for diagnostics*, of the option *Automatic Control and Industrial Computing*, at the École des Mines de Nantes, since January 2000.

She has delivered a course [101] within a Ph.D. program on *Fault Detection for Control and Signal Processing*, at Aalborg University, DK.

10 Relevant publications of the team

Books

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