Abstract of Research Project

XXXV Cycle (A.Y. 2019-2020)

Name of fellow: Enrique García Macías

Name of UNIPG Supervisor: Filippo Ubertini

International Partner Institution: Imperial College - UK

Name of International Co-Supervisor: Dr. Emilio Martinez Paneda

Start Date: 1.11.2019 **End Date: 31.10.2022**

RESEARCH PROJECT (max 3 pages):

Introduction and state of the art

The management of ageing infrastructures represents one of the most pressing challenges of Structural Engineering. A sizeable proportion of European civil infrastructures were built during the economic growth of the 1930s, thus they are currently approaching their design service life. Recent tragic events such as the collapse of the Genoa Bridge in 2018 have evidenced that normal degradation processes definitely represent a severe hazard for infrastructures. To give an idea about the magnitude of this problem, the last Infrastructure Report Card of the American Society of Civil Engineers [1] classified about 9% of the more than six hundred thousand American bridges as structurally deficient, and estimated the corresponding rehabilitation costs at $123 billion dollars. The enormous socioeconomic impacts derived from the management of ageing infrastructures require the implementation of reliable and effective maintenance strategies. Traditional periodic inspection policies have proved inefficient in terms of cost and detection of early-stage structural pathologies. These are often performed through visual surveying, which requires the work of experienced technicians and can hardly detect defects that do not manifest in the surface. Condition-based maintenance strategies within the framework of Structural Health Monitoring (SHM) constitute a powerful alternative. Through permanent monitoring and suitable damage detection tools, rehabilitation tasks can be scheduled according to the real-time condition of structures, thereby minimizing the number of inspections and repairing risky pathologies at early formation stages. Despite the numerous reported benefits of such systems, their application to civil infrastructures remains very limited. This is chiefly due to the need of important initial investments on monitoring equipment, data management, as well as the assistance of highly qualified experts in signal processing and data mining, what dissuades infrastructure managers with low returns on their investments.

Vibration-based SHM systems have become specially popular owing to their effectiveness for non-destructive global damage detection and minimum intrusiveness [2]. Such systems rely on the identification of the modal features (i.e. resonant frequencies, damping ratios, and mode shapes), which depend upon the intrinsic stiffness and energy dissipation mechanisms of structures. Therefore, the appearance of damage affecting the overall stiffness of structures can be detected by means of variations in the modal properties. In this line, monitoring systems based on Output-only or Operational Modal Analysis (OMA) are specially engaging. These rely on the assessment of ambient vibrations without the need of any artificial excitement source, thereby the monitoring can be performed in operative conditions without interfering in the normal functioning of structures [3]. Such systems are notably well-suited for cultural heritage structures, where monitoring must not only ensure that safety needs are met, but also they must respect the architectural value of the structure. In this light, numerous successful applications can be found in manifold structural typologies, such as bridges [4], dams [5], wind turbines [6], and historic constructions [7]. Despite the great level of development of these techniques, their technological transfer to common practice is still at very initial stages. This is largely due to the following key limitations:

- Difficult automation of damage detection algorithms. Damage detection using vibration-based SHM is usually performed by tracing the time series of certain statistical distances of the resonant frequencies with respect to a baseline undamaged condition (e.g. design specification or an initial training period). Such distances are plotted in a control chart along with a user-defined threshold indicating some statistical confidence level. In this way, damage detection reduces to a two-class classification problem, that is to say, the system only differentiates between control and out-of-control data points (see e.g. [8]). This leads to elevated false alarm rates and requires the assistance of highly qualified operators. In addition, such an approach impedes the identification of varying operational conditions and, most importantly, the identification of damage-induced variations in the structural sensitivity to environmental factors. Therefore, these techniques usually fail at detecting multiple damage scenarios.

- Limited effectiveness at detecting local structural pathologies. While vibration-based SHM systems are highly effective for detecting global defects, local damage sources with minimum impact over the overall stiffness of structures are hardly identifiable. A wide variety of local deterioration processes can be found in common practice, such as, among others, chemical (e.g. carbonation, chloride penetration, sulphate attacks, freezing/thawing deterioration, etc.) and electrochemical (corrosion) attacks. Such phenomena are more effectively detected by non-vibration non-destructive testing techniques (e.g. static monitoring, electrical resistivity measurements, acoustic emission, etc.). Therefore, next-generation SHM systems with local/global damage detection capabilities must be aggregated, that is to say, they must fuse the information retrieved from heterogeneous sensing solutions.

- Troublesome application for damage localization. Vibration-based SHM systems are highly effective for damage detection, while their application to damage localization remains an intricate task. This typically implies the inverse calibration of a numerical model. To do so, some damage sensitive parameters of the model must be fitted in order to reproduce the experimentally identified modal features. In this line, some successful applications can be found on frame or truss structures, whilst the updating of 3D numerical models is usually very challenging and computationally demanding. This is particularly critical in historic constructions whose geometrical complexity often demands densely meshed models. Such difficulties preclude their application to online model calibration. Therefore, it is often impossible to filter out the effects of environmental and operational conditions from the fitting parameters and, as a result, effective damage localization becomes impractical.

Research objectives

In view of the previous state-of-the-art review, this research project is aimed at developing new autonomous aggregated SHM systems with superior damage detection and localization capabilities. To do so, several strategic objectives (**OB**) have been established in order to cope with the previously reported limitations of conventional vibration-based SHM systems. These include:

OB-I: Development of automated normalization (elimination of operational and environmental effects), pattern recognition and novelty analysis techniques for aggregated SHM systems. This will involve new software solutions for the development of autonomous SHM systems involving heterogeneous sensing techniques.

OB-II: Development of new semi-supervised classification algorithms for multi damage detection of aggregated SHM systems. Through non-parametric clustering, efforts will be devoted to the development of automatic pattern recognition of multiple damage sensitive features. These include not only modal information, but also monitoring data from different sensors such as static, environmental, and/or chemical sensors.

OB-III: Development of new data fusion techniques capable of performing pattern recognition of multiple long-term monitoring systems. Most efforts will be devoted to the identification/elimination of environmental/operational factors and automated non-parametric clustering for multi-damage detection of multiple damage sensitive features.

OB-IV: Development of surrogate-based model updating approaches for automated online damage identification. Specially framed for geometrically complex historic masonry structures, this objective is aimed at developing computationally efficient surrogate models for calibration of intensive 3D numerical models. In this light, some of the previously developed pattern recognition and classification approaches will be applied to the time series of continuously updated model parameters for automated damage localization.

Methodology

The methodology has been designed to achieve a leading-edge technological transfer. This includes not only all the fundamental aspects involved in the previously listed objectives, but also their direct application on real infrastructures. To do so, provisions have been already made to secure the access to different constructions. In particular, some of the developed techniques will be applied to the monumental Consoli Palace in Gubbio within the framework of the PRIN project "DETECT-AGING - Degradation effects on structural safety of cultural heritage constructions through simulation and health monitoring" (protocol no. 201747Y73L)". This structure will represent a benchmark case study of this research project, since it will be monitored with a dense mixed SHM systems, involving both dynamic, static, and environmental sensors. Additionally, we already have held some initial meetings with ANAS, and we count on their support to conduct some collaborative works on the development of automated SHM systems for damage assessment of bridge structures.

The research plan has been organized according to four work packages covering the previously stated objectives.

WP-I: Software solution for automated signal processing, data normalization, pattern recognition and novelty analysis. The code to be developed will have to allow the automatic analysis of multiple damage sensitive features and perform parallel novelty analysis. The success of this WP will be evaluated through its application to the case study of the Consoli Palace.

WP-II: A novel non-parametric clustering approach will be developed to detect multiple damage scenarios. The developed approach will be tested through simplified numerical tests, as well as through experimental time series obtained from the Consoli Palace and non-linear simulation analyses of a 3D numerical model.

WP-III: New data fusion techniques will be developed to incorporate the processing tools developed in WP-II into the software environment designed in WP-I. Research efforts will focus on the use of multi-dimensional time series of monitoring data for pattern recognition and data normalization. This will allow the definition of several damage sensitive features characterizing both global and local properties of structures. Finally, the non-parametric clustering approach will be incorporated to perform automated damage detection. The success of this WP will be evaluated through numerical case studies.

WP-IV: Development of an innovative surrogate-based model updating approach for automated damage localization in geometrically complex historic structures. In particular, great efforts will be developed to the accurate training of computationally inexpensive surrogate models, as well as the analysis of ill-conditioning limitations in the inverse calibration problem. The developed approach will be validated through non-linear simulation analyses and experimental results obtained from the Consoli Palace.

The dissemination of the scientific achievements represents an essential element in this research project, including journal publications, public engagement activities and social media. With regard to the elaboration of scientific publications for peer-reviewed journals, the strategy is to prioritize quality over quantity.

Expected results

In general terms, this research project is envisaged to represent a groundbreaking breakthrough towards the development of autonomous aggregated SHM systems. In particular, this research project is expected to provide the knowledge and suitable software tools for implementing and exploiting fully autonomous aggregated SHM systems with superior damage detection and localization capabilities. This is anticipated to lead to a major impact on the construction industry and, possibly, the success of the project will generate future research funding opportunities.

Bibliography

[1] ASCE (American Society of Civil Engineers). (2017). Infrastructure Report Card. Reston, VA, USA: ASCE.

[2] Chen, H. P., & Ni, Y. Q. (2018). Structural health monitoring of large civil engineering structures. Hoboken, NJ: Wiley Blackwell.

[3] Brincker, R., & Ventura, C. (2015). Introduction to operational modal analysis. John W.

[4] Magalhães, F., Cunha, A., & Caetano, E. (2012). Vibration based structural health monitoring of an arch bridge: from automated OMA to damage detection. Mechanical Systems and Signal Processing, 28, 212-228.

[5] Pereira, S., Magalhães, F., Gomes, J., Cunha, Á., & Lemos, J. V. (2017). Installation and results from the first 6 months of operation of the dynamic monitoring system of Baixo Sabor arch dam. Procedia engineering, 199, 2166-2171.

[6] Ubertini, F., Comanducci, G., & Cavalagli, N. (2016). Vibration-based structural health monitoring of a historic bell-tower using output-only measurements and multivariate statistical analysis. Structural Health Monitoring, 15(4), 438-457.

[7] Magalhães, F., & Cunha, Á. (2011). Explaining operational modal analysis with data from an arch bridge. Mechanical systems and signal processing, 25(5), 1431-1450.