Bayesian Inversion of a Non-linear Dynamic Model for Stockbridge Dampers

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Abstract. Stockbridge dampers are the most widely used in wind induced vibration control of overhead power transmission lines. This dynamic absorber comprises a carrier cable with a mass at each end and a bolted clamp that can be attached to a conductor or a guard wire, with the purpose of supplementing the energy dissipated by the cable related to its self-damping. The maximum response of this type of absorber is associated with the frequencies of its different oscillation modes. The masses are designed in such a way to obtain moments of inertia and location of their center of gravity such that, with the vibration of the clamp, their various characteristic bending and torsional modes are excited. In this work, the calibration of a nonlinear finite element model using Bayesian inference is presented to evaluate the dynamic behavior of the damper for all excitation frequencies and displacement amplitudes. To this end, an inverse problem was posed in which the probability distributions of the parameters of interest are obtained from backward uncertainty propagation of experimental measurements performed in laboratory tests. Finally, the uncertainty of the calibrated model was propagated and contrasted with the experimental data. The developed model is a powerful tool when defining the quantity and distribution of dampers in the span of a line.

Keywords: Aeolian vibrations · Stockbridge damper · Bayesian calibration · Inverse Problems · Uncertainty Propagation

1 Introduction

During the operation of overhead power lines for electric transmission, the conductors as well as the guard filaments are subjected to several classes of mechanical vibrations such as: galloping, Aeolian, and subspan oscillations [1] for bundled conductors. The so-called Aeolian vibrations (generated by von Karman vortex shedding [2]), are the most dangerous because they cause fatigue failures in cable filaments and support accessories. Such failures are observed in the supporting clamps or dampers clamps because of high alternative bending stresses.

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Due to the high capital investments involved in the line projects, it is necessary to pay special attention to the potential failures that vibrations can cause on the cables. The Stockbridge type damper has been used successfully to reduce of wind vibrations. Figure 1 shows an installation of the Stockbridge on a guard wire (Fig. 1(a)) and a scheme for experimental tests (Fig. 1(b)). The employment of appropriate mathematical models to analyze this type of problems is quite relevant. Since the dynamic response of the Stockbridge is non-linear and hysteretic (due to internal friction in the cable wires), various models of increasing complexity have been proposed [3].

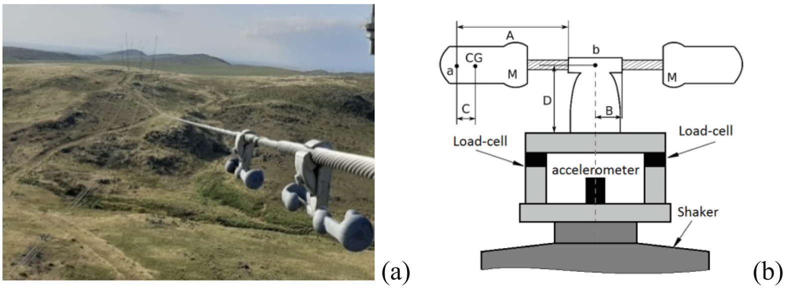


Fig. 1. (a) Detail of an installation of Stockbridge-type damper in a guard wire. (b) Test-rig set-up for the identification procedure of the Stockbridge.

In order to analyze the system cable-damper, Barry [4] developed a simple analytic model in which the cable is conceived as a beam subjected to axial loads and the damper is reduced to a lumped mass-spring-dashpot approach. Subsequent models [5] considered a coupled double beam where the cable is the main beam and the Stockbridge is modeled as a beam with a rigid mass attached to each end. A geometrically non-linear conception and viscous structural damping of the messenger cable have been incorporated into the model; moreover, experiments have been conducted to validate the approach and equivalent values of the parameters (e.g. damping coefficient, natural frequencies of the cable with and without the damping system, etc.) have been calculated as well. Although the non-linear model is evidently time-demanding, it gives quite good predictions of the dynamics. In other studies, non-linear finite elements were involved by considering the hysteresis phenomenon [6].

In the present article, a computational approach of a given Stockbridge is constructed and aimed to identify parameters with the final objective to study the uncertainty propagation in its dynamics. The Stockbridge is conceived as a non-linear finite element beam model subjected to movement in a plane. The intrinsic hysteretic non-linearity of the messenger cable as well as the structural viscous damping, are incorporated. A Bayesian inversion technique is employed to identify parameters of the model, which are quite difficult to measure directly (e.g. cable stiffness, bending moments of individual filaments, etc.). The procedure is explained in the second section. As the parameters of the Stockbridge can have variability due to many circumstances (approaches to identify and calculate the dynamics, constructive gaps or assembly discrepancy under service, etc.) and given that Bayesian Inversion is time-consuming, a study of the uncertainty propagation of the parameters is performed as well.

2 Methodology

As mentioned before several parameters of a Stockbridge model are difficult to be identified by direct experimental tests, consequently, a Bayesian inversion method is employed. This approach, based on Bayes' theorem, requires an appropriate predictive deterministic model, a physical system to extract experimental values and a probabilistic approach. Figure 2(a) shows a diagram of the Bayesian inference procedure to estimate parameters of a model. Figure 2(b) shows the structure of the whole procedure of this article, i.e. first an identification process and then the uncertainty propagation; μ, ε, δ, and λ are the parameters to be identified (see Sect. 2.3).

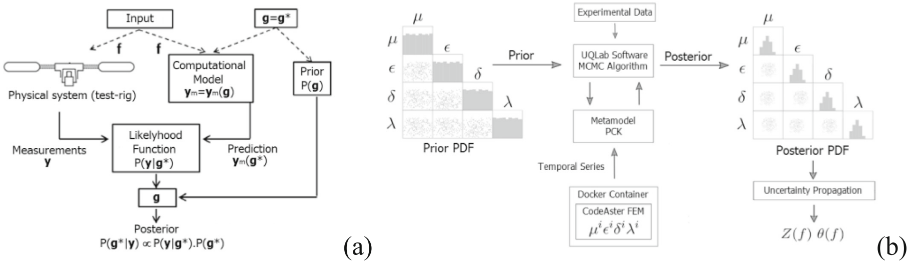


Fig. 2. (a) General scheme of the Bayesian inference approach. (b) Present computational scheme based in the UQLab procedures.

In Fig. 2(a), **y** is the vector of experiments (under test frequency **f**); **g** is the vector of parameters in the predictive model $\mathbf{y}_m(\mathbf{g})$; **g*** is a vector of proposed parameters, P(**y**) is the probability density function (PDF) of **y**, P(**g**) is the PDF of the parameters, P(**y**|**g***) is the PDF (or likelihood function) of **y** given **g***.

2.1 Experimental Test-Rig

The Stockbridge was subjected to the vibratory loads of an electro-dynamical shaker according to the International Standard IEC 61897 [7]. This standard requires a frequency sweep with constant speed. The mechanical Impedance (Z) of the Stockbridge is measured; the force in the damper clamp (F) and the excitation speed ($\dot{x}$) are measured as well. In Eq. (1) one can see expressions of the Impedance and phase angle (θ).

$$Z = \frac{F}{\dot{x}}, \quad \theta = arg(Z) \tag{1}$$

According to Fig. 1(b), the force in the clamp is measured by means of two load cells (type HBM U9C). The speed of the clamp is measured with an accelerometer (Brüel & Kjaer Delta Tron 4507 B004) by integrating the signal. This measuring configuration avoids spurious moments and shearing displacements, allowing absolute direct data which is registered in the Acquisition System HBM QuantumX. The frequency sweep is carried out in discrete steps and the experimental signals are processed with Fourier transformation by means of an "ad-hoc" routine developed by the authors for this particular study.

2.2 Brief Description of the Predictive Deterministic Model

In the present article, the non-linear dynamics of the Stockbridge is computed by means of non-linear beam finite element of the open-source software CodeAster [8], that the authors modified and adapted in order to incorporate the variation of the stiffness along the beam. This is done by coupling several types of beam elements. The messenger cable is modeled by a linear elastic beam element coupled to other beam elements that have an ideal elastoplastic behavior. This conception is aimed to take into account the stick-slip of inner filaments [9]. The bending stiffness (EI) of the messenger cable is an important parameter for the dynamical response and its behavior is related to the curvature (κ). The bending stiffness varies between EI_{min} (where filaments can slip freely and only the stiffness of each filament with respect to its local neutral axis is taken into account) and EI_{max} (where all filaments are stuck as a solid body). The bending moment (M_f) can be approximated by Eq. (2), where the bending stiffness is calculated according to the stick-slip variation along the beam with Eq. (3).

$$M_f \approx EI\kappa, \forall EI = fnc(\kappa) \tag{2}$$

$$EI = EI_{max} = EI_{\min} + EI_{stick} \quad or \quad EI = EI_{\min} + EI_{slip} \tag{3}$$

It has to be mentioned that under a cyclic load one can observe the hysteretic behavior that is responsible for the energy dissipation in the system. The Newmark-beta method is used to integrate the finite element equation $\boldsymbol{M\ddot{U}} + \boldsymbol{D\dot{U}} + \boldsymbol{KU} = \boldsymbol{F}$, where $\boldsymbol{M}, \boldsymbol{D}$ and $\boldsymbol{K}$ are the global matrices of mass, damping and stiffness, respectively; whereas $\boldsymbol{F}$ is the vector of forces and $\boldsymbol{U}$ the vector of kinematic variables. Due to space restrictions, the mathematical formalism of the beam finite element model cannot be expressed, however, the interested readers are invited to look into [8, 9].

2.3 Brief Description of the Stochastic Approach

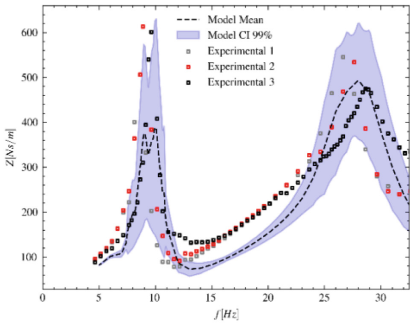
As explained in Sect. 2.1, in order to infer the input parameters $\mathbf{g}$ of the structural system, the experimental data $\boldsymbol{y} \in R^N$ (N is the number of independent tests) are such that $\boldsymbol{y} = \boldsymbol{y}_m(\boldsymbol{g}) + \varphi$,where $\boldsymbol{y}_m(\boldsymbol{g})$ is the mathematical representation of the system (or predictive model) and the term φ represents the discrepancy between experimental data and the predictive model [10]. The Bayesian Inference requires the proposal of prior PDFs of the parameters to be identified. This can be done by applying the Maximum Entropy Principle based on given information about the physics of the problem. In the present study, the following parameters are considered stochastic: μ (bending stiffness of external filaments), ε (eccentricity of the lumped mass), δ (bending stiffness of the messenger cable core), λ (limit bending moment of the external filaments).

The Bayesian Inversion procedure employed in this article appeals to a Markov-Chain Monte Carlo simulation through the Metropolis-Hastings algorithm implemented with the software UQLab [11]. The direct use of this procedure requires a lot of realizations of the deterministic predictive model for the aleatory input parameters. In order to reduce the computational cost, a meta-model was implemented (by means of the predictive deterministic model) to evaluate the dynamic response of the Stockbridge. Among all the available platforms to construct the meta-model, in this article the Polynomial-Chaos-Kriging (PCK) approach is employed [12].

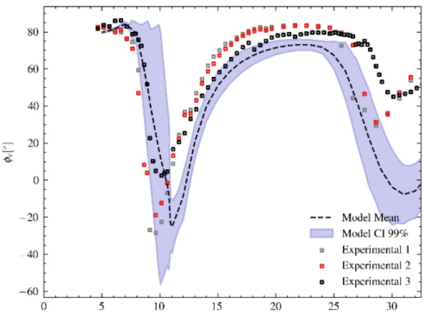
Finally, once the parameters are identified (and consequently their posterior PDFs), the propagation of uncertainty is carried out by means of realizations of the predictive model whose sampling is performed in the frame of the Latin Hypercube method.

3 Casuistic Study and Results

In this section, a particular Stockbridge as the one sketched in Fig. 1(b) is evaluated. Since some data is not available from the manufacturer, A, B, C, D and M have been gathered from a 3D solid model employing the measuring tools of the CAD software Solidworks™. The following values were obtained: A = 0.138 m, B = 0.030 m, C = 0.020 m, D = 0.088 m, M = 0.640 kg. With these values, it is possible to calculate realizations in the predictive deterministic model and/or the PCK meta-model. The calibration of the PCK meta-model was carried out from 81 evaluations of the numerical deterministic model at 32 frequencies of interest (from 5 Hz to 37 Hz).



(a)



(b)

Fig. 3. Experimental results and uncertainty propagation (a) Mechanical impedance. (b) Phase angle of the impedance.

Figure 3(a) and Fig. 3(b) show the uncertainty propagation of the Impedance and its phase angle, respectively; for the calibrated numerical model contrasted with the experimental data. A good fit of the predictive model with the experimental info of the damper in the frequency range of interest is evidenced. In this sense, it should be noted that the resonance frequencies of the model, both flexional (first mode) and torsional (second mode), correspond satisfactorily with the experimental observations. The uncertainty propagation of the angle phase fits adequately the experimental data in most of the frequency range. However, discrepancies appear in higher frequencies, after the second resonance mode. Notice that after 25 Hz, there is divergence.

4 Conclusions

The proposed methodology allows modeling the non-linear dynamic behavior of the Stockbridge considering the variability of the design nominal parameters. By applying the PCK meta-model, the computational cost associated with the evaluation of the inverse problem (and/or parameter identification) is significantly reduced. The quantification of the uncertainty allows evaluating the variability of the Stockbridge response.

Finally, the computational tool developed will allow the assembly of the Stockbridge model in a global system of finite elements of increasing complexity, such as the cable-damper assembly, in order to analyze the vibrational behavior against wind actions of a stochastic nature. In particular, it is proposed to evaluate in future works the reliability of the damping system of the line from the application of numerical optimization techniques. Moreover, other stochastic methods (such as Non-parametric Probabilistic Approach) and enriched beam non-linear formulations are being evaluated to extend the analysis of the Stockbridge, but this is part of a forthcoming paper.

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