Proper Orthogonal Decomposition Analysis of Impact-Induced Dynamics of the Olive Tree Branch: A Paradigm of a Complex Soft-Stiff Structure in Biomechanics

Ioannis T. Georgiou
School of Naval Architecture & Marine Engineering, Laboratory of Dynamics-Acoustics & Diagnostics of Complex Structures, National Technical University of Athens, Athens, Greece

Summary. Geometry consistent spatio-temporal measurements of the experimental acceleration of olive tree branches were analyzed with advanced POD tools in an effort to gain knowledge on the dynamics of this bio-mechanical structure. To pave the way for understanding this system, both the typical olive tree as a whole and its typical branch are approached as interacting soft-stiff continuum systems. The POD analysis reveals that the impact response is a nonlinear vibration with very fast dissipation. The POD modal amplitudes are nonlinear vibrations of continuous, broadband frequency spectrum. Initially they exhibit regular phases of nonlinear slow dissipation-and-amplification followed by irregular, fast dissipation-and-amplification phases. Sequentially applied impacts at the branch soft area results in a complete detachment of the fruit. The POD analysis reveals that this occurs because the response is highly localized in the soft area where the impact is applied and thus it transfers its momentum to the fruits.

Viewing the Biological Olive Tree as a Complex Soft-Stiff Mechanical Structure

The olive tree is one of the most precious gifts of Mother Nature to humans. As such farmers-on a continuous basis-are facing the issues of the sustainment of high yield and economic harvesting, the latter being related to the dynamics of the tree. Is the detachment of the fruit more effective when the tree is forced by a shaker (modernization) of when it accepts repeated impacts (tradition)? We could answer this question if we learn how elastic waves propagate in this highly dissipative, nonlinear system-being both complex and diverse. Both brute force modelling and experimental vibration studies appearing in the literature have limitations [3,4]: linear dynamics with missing connections. These could be remedied if we take into account the intrinsic structural architecture of the tree. Modern Nonlinear Dynamical supports such an approach via the concept of *soft-stiff* structural systems. Figure 1a is a photographic view of productive trees from an olive tree orchard in Greece. Its structural architecture is underlined by the following characteristic: From a naturally cantilevered stiff trunk several soft branches bifurcated to form a soft canopy. The typical branch ends with a collection of softer sub branches with leaves and fruits, the organs. Both at the level of the tree and the level of the branches we have a bio-mechanical structure formed of *soft* beams stemming naturally from a central *stiff* beam. The class of stiff-soft structural systems can be analyzed by *Slow-Fast Time Decomposition*: the vibration modes of soft-stiff systems stem from the submodes of the decoupled substructures and admit qualitative changes when the slow-fast invariant manifolds bifurcate [1]. Figure 1b shows a lab set-up for measuring the impact dynamics of a cantilevered olive tree branch. The local normal acceleration response due to impact is sampled simultaneously at several locations. This geometry consistent space-time sampling of free dynamics is analyzed by advanced POD tools [2]. The computed intrinsic POD modes contain physics relevant information, Fig. 2.


Figure 1 (a) productive olive trees in an orchard in Western Peloponnese, Greece. (b) Laboratory tested olive tree branch instrumented with sensors for vibration measurements.

Conclusions

Single impacts at the interior (stiff) and multiple impacts at the organs bearing area (soft) of the tested olive tree branch give POD energy spectra co-dominated by several POD modes, see Fig. 2a-b. Impacts of different magnitudes reveal via POD tools that the impact-induced free dynamics are nonlinear. The amplitudes of the POD modes are waveforms with fast decay. For impact excitation in the fruit and leaf bearing area (soft) the POD implodes have broader spectrum, Fig. 2e (green), than the case where the impact is applied in the interior (stiff) of the beam, Fig 2e (black, red). The remarkable results is that the POD shape of the dominant mode (50% of energy) is localized whenever the single impact or set of impacts is/are in the soft part of the beam, Fig. 2d and not localized when the impact is in the stiff interior area, Fig. 2c. Farmers, by using a wooden stick since ancient times, are still applying rhythmic impacts to this part of the branch to detach the precious fruit. We consider the olive tree structure an excellent paradigm for sensory data-based knowledge discovery in bio-mechanical structures with quite complicated geometric features (spatial complexity). Furthermore, the intrinsic structural characteristic *of interacting soft and stiff substructures* motivates theoretical advances of the *Slow-Fast Time Decomposition Theory* to analyze the simulated and/or the experimental dynamics of complex structures.

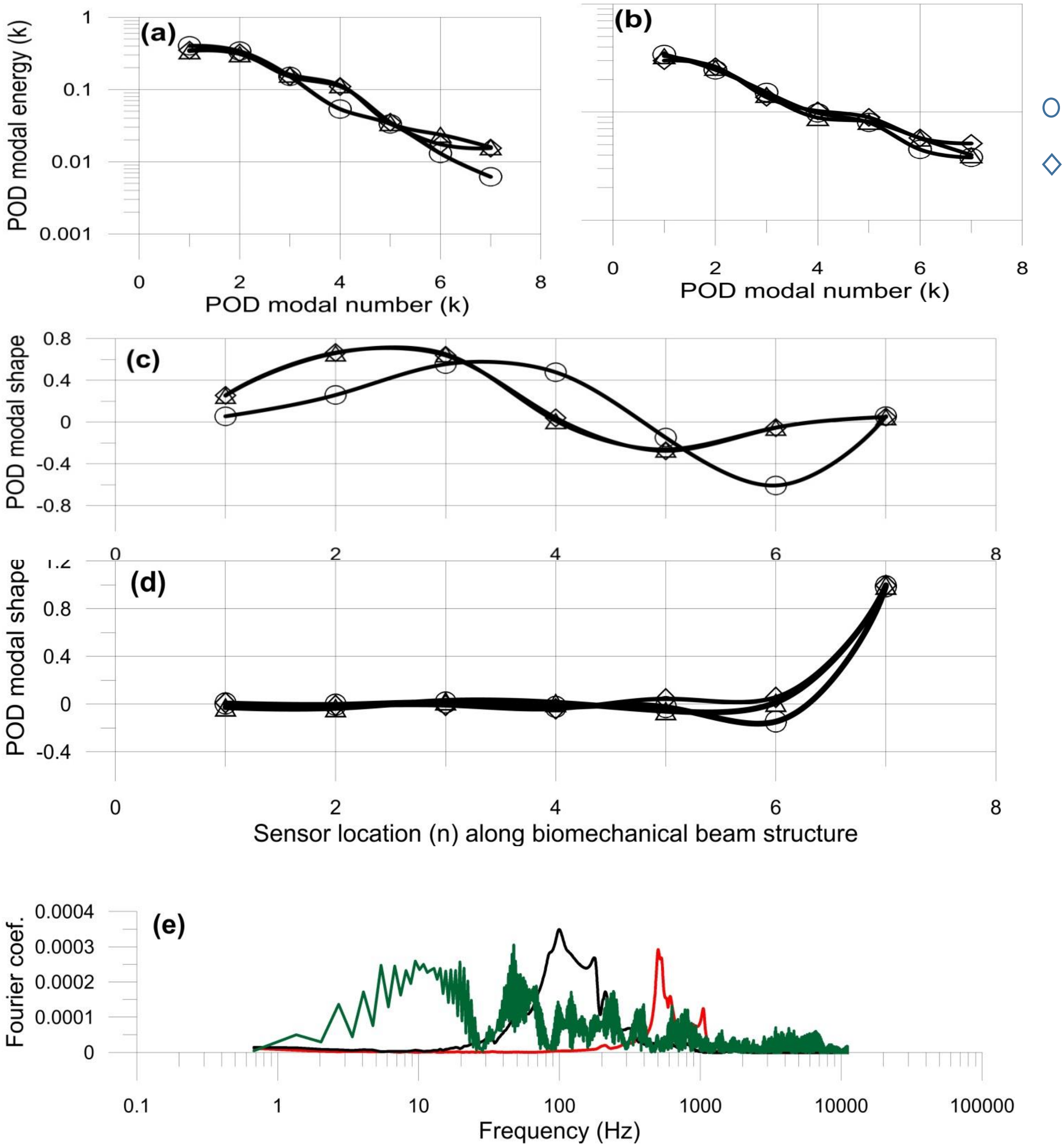

Figure 2 Computational results of the POD transform of the experimental free dynamics-at the level of acceleration-of the olive tree branch in Fig. 1b. (e-green) a broadband spectrum covering low and high frequencies

References

[1] Georgiou I. T. (1999) On the Global Geometric Structure of the Dynamics of the Elastic Pendulum. *Nonlinear Dynamics* **18***:* 51-68.

[2] Georgiou I. T. (2005) Advanced Proper Orthogonal Decomposition Tools: Using Reduced Order Models to Identify Normal Modes of Vibration and Slow Invariant Manifolds in the Dynamics of Planar Nonlinear Rods. Nonlinear Dynamics 41: 69-110.

[3] Castro-Garsia S., Blanko-Roldan G., Gil-Rides J., Aguera-Vega J. (2008) Dynamic Analysis of Olive Trees in Intensive Orchards Under Forced Vibration. *Trees*: 795-802.

[4] Bentaher H., Haddar M., Fakhfakh T., Maaej A. (2013) Finite Element Modeling of Olive Tree Mechanical Harvesting using differrnt Shakers *Trees*: 1537-1545.