EUROPEAN MECHANICS SOCIETY

Colloquium No 562 Scientific Report

The studies on the dynamics of nonlinear systems show that, when the nonlinearities are explicitly considered in the calculations, not only they allow a correct understanding of the behaviour, but they can also be exploited to improve the performance. Both controlled and uncontrolled systems are analysed, and the stability issues are addressed. The modelling of the mechanical system is recognized as a key ingredient, and problems are formulated at either the macro or micro scale. For example, a plethora of nonlinear phenomena observed in macrostructures are waiting to be observed and exploited for mass sensing at the microscale. Pull-in, sudden collapse of electrostatic MEMS, or any other unsafe bifurcation, sub-critical pitchfork or cyclic fold bifurcation, can be used as a mass detection mechanism in binary chemical and biological sensors. At the macroscale, the large amplitudes dynamics of rotating pendula, delayed van der Pol oscillators, and bistable oscillators are studied toward energy harvesting applications. Moreover, the nonlinear dynamics and the modal stability of cables, beams, moving strings, discrete systems with a large number of DOFs, towers, under both conservative and nonconservative actions, are deeply investigated toward the discovering and understanding of their rich bifurcation scenarios. To this end, also the study of classical paradoxical systems is addressed. Further topics discussed in the talks are summarized as follows.

A) MODELLING ISSUES IN STABILITY AND BIFURCATION OF DYNAMICAL SYSTEMS

The modelling of both the complex mechanical structures and the external actions are crucial points for the analysis of the stability and post-critical behaviour of dynamical systems. Reduced models are shown to be useful for this aim since, in a quite large variety of applications, as the ones briefly recalled in the following, they are able to capture the essential dynamical phenomena. In particular, the tower buildings, for which the dynamic analysis is usually carried out numerically through sophisticated finite element models, are studied through simplified models, such as an equivalent nonlinear one-dimensional shear-shear-torsional beam model embedded in a three-dimensional space. Analogously, thin-walled members are described through added kinematical descriptors in the framework of the Generalized Beam Theory; a new method is consistently proposed in order to introduce nonlinear modes which are able to describe the modifications of the sole transversal shapes. Moreover, also the dynamical characteristics of (composite) rotating beams are studied via a reduced model for selected configurations, aiming to check the importance of the longitudinal displacement and the coupling inertia forces (including Coriolis force) on the amplitudes of the remaining coordinates. On the other hand, concerning complex external actions, it is also of interest to investigate and understand the complex nonlinear and non-stationary spatio-temporal dynamics of flexible and elastically restrained rigid-bodies immersed in a uniform flow, and the time-periodic dynamic behaviour of a cable-like system under steady wind.

B) UNEXPECTED PHENOMENA IN NONLINEAR DYNAMICAL SYSTEMS

Unexpected phenomena sometimes can manifest themselves in nonlinear systems. In particular, the ones discussed at the Colloquium concern: (1) tensile instability in beam-like structures, such as an Euler Bernoulli beam in the presence of an arbitrary number of internal sliders endowed with translational elastic springs for nonconservative tensile axial load; (2) interactions between Nonlinear Normal Modes and linear frequencies, which are responsible for the isolated resonance curves in the forced response, and are important, from a practical point of view, in either numerical continuation or experimental testing; (3) static and dynamic stability of a thin rod under axial compression for which, in the cases studied by Lavrentiev and Ishlinsky, if the magnitude of the axial jump loading coincides with the *n-th* Euler buckling load, another buckling form rather than the *n-th* one has the maximal rate of lateral instability.
Some celebrated paradoxes, related to follower actions in one-dimensional systems are also addressed. In particular, one recalls: (i) the Nicolai beam, modelled as a nonlinear, internally constrained one dimensional polar continuum embedded in a 3D space, is analysed and the post-critical behaviour, showing the presence of large-amplitude limit cycle on the system's response, is observed; (ii) the nonlinear Ziegler column and the Beck beam, both endowed with proper form of nonlinear damping, are investigated through a suitable perturbation procedure and the role played by the damping on the critical and post-critical behaviour (limit-cycle formation) is highlighted.

C) VIBRATIONS CONTROL IN OPERATIONAL CONDITIONS

In controlled systems, the task of vibrations mitigation can be pursued by either passive, active or semi-active strategies. For example, semi-active management and redistribution of potential energy has been investigated for the mitigation of impact born vibrations in structures with controllable truss-frame nodes by using a prestress accumulation-release strategy: a dynamic local structural reconfiguration which changes the bending moment bearing ability of the nodes occurs via on/off control. MR (magneto-rheological) dampers can be tested in different configurations: passive-on, skyhook semi-active, and emulated negative stiffness; when they are

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mounted as secondary suspensions in high-speed trains, the latter configuration has been shown to perform the best. The semi-active control option offered by MR dampers can be usefully applied to realize a time variant restraint at the base of a wind turbine tower with the aim of protecting it from strong winds. Wide frequency band vibrations reduction in wind-excited high rise buildings can be effectively pursued in a passive manner by the use of particle tuned mass dampers which permit to dissipate the input energy through tuned mass plus the friction and the impact between particles and the wall of the containers. The highly non-linearity of phenomenon, and the presence of noise and impact force, call for the development of practical design methods based on experiments and numerical methods.
Including the nonlinearities in the design of the controllers is often a difficult process, which is however fundamental to ensure a correct performance. Relevant research efforts are dedicated to the development of simplified modelling techniques. For example, a formulation of the TLCD (tuned liquid columns damper) controlled systems using fractional derivatives is shown to allow a good agreement with the experimental results; furthermore, since the proposed model is linear, the system parameter identification is extremely simpler than the classical nonlinear one. Identification and estimation of nonlinear hysteretic systems is a critical challenge, because the nonlinear restoring forces cannot be expressed as algebraic functions of instantaneous variables due to the “memory” of the hysteresis; within this context, the Volterra/Weiner neural network represent an adaptive, data-driven, online estimator. When finite element models of large civil structures with nonlinear hysteretic behaviour are considered, the adoption of model order reduction techniques which preserve the dynamical features of the underlying high dimensional, second-order system is of great interest.
Slender footbridges with either a cable-stayed or suspended structural scheme and a span greater than 100 m represent a convenient test-bed for active control solutions due to their high sensitivity to dynamic actions. In particular, the variation of the tension in the stays under human induced loading and its effects on the deck’s modal features suggest to resort to either piecewise linear or fully nonlinear active control algorithms which are able to cope with a time varying space matrix. Alternatively, simple prediction formulae based on linear models may be used for the design of decentralized active tendon control of cable-structures, but they must be supported by experiments.

D) MOTION TRACKING CONTROL

The development of tension control strategies aiming to steer a tethered satellite from a position close to the main station to another position further down in minimal time and allowing for tether oscillations is discussed. The detrimental effects of a local

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external feedback control on the global stability of an atomic force microscope (AFM) are assessed using dynamical integrity measures; the aim is to properly identify the design parameter ranges able to guarantee the secure operation of the controlled AFM. The control objective of programmed motion tracking is formulated as follows: given a reference motion specified by the constrained dynamics, design a feedback controller that can track the reference motion. The model-based control of third order nonholonomic systems can be approached on the basis of a multi-purpose modeling framework for constrained mechanical systems which uses the generalized programmed motion equations method. The reference dynamics are employed to design a tracking control strategy for constrained motions, so that the framework can be seen as an input to an "advanced control platform", which is a fusion of modern control oriented modeling, control algorithms and embedded controllers.
The task of shape control and vibration morphing of a pre-deformed structure can be accomplished by smart actuation such that the incremental displacements coincide with some desired time-dependent small (infinitesimal) displacement field with corresponding small deformations. The incremental actuation stress is taken as a linear mapping of actuating non-mechanical fields, such as the electric field or temperature in a thermo-piezo-elastic body. First, the three dimensional case is discussed and then the solution strategy is exemplified with reference to a single-degree-of-freedom oscillator with a cubic restoring force, starting from rest, and a thermally pre-deformed beam with hinged-hinged, axially fixed supports. The nonlinear behaviour of thin plates with embodied piezoelectric transducers is studied; the stability of the equilibrium and the post-buckling behaviour are discussed.

E) LIMIT CYCLE CONTROL

When the control objective consists of the stabilization of the system by suppressing or reducing its limit cycle oscillations, the coupling of the main system with a nonlinear energy sink (NES) is considered as an effective passive control strategy. The particular case in which the main system is a oscillator with hardening elasto-plastic behaviour is discussed. The NES effectiveness in controlling the nonlinear aeroelastic response of a pitching-plunging airfoil is also assessed. A nonlinear tuned vibration absorber, which combines the concepts of the linear absorber and the nonlinear energy sink, is proposed for the suppression of self-excited (limit cycle) oscillations: the linear part enlarges the stability region, and the nonlinear one is introduced to avoid bistability in a van der Pol-Duffing oscillator. The possibility of adopting piezoelectric dampers in the presence of not conservative loads to control the limit cycle of the Ziegler column is investigated.

F) GENERALIZED CONTINUA

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Generalized continua are discussed in a dedicated session as a powerful tool for the description of newly conceived materials and complex structures, such as the biological systems. Metamaterials are among the most promising and rapidly developing research areas, and the link between theoretical aspects and new possibilities in computer-aided manufacturing is of great interest. Experimental evidence shows peculiar effects in metamaterials which cannot be described by means of ordinary Cauchy continua. The mechanics of fabric sheets represents a particular case of this kind, for which it is possible to build a general model leading to a non-standard strain-gradient effect in the elastic response. A discrete approach to higher gradient models is also possible if one considers sets of elements having a centroid-based interaction and keeping memory of their original configuration. Numerical evidence shows that these kinds of models are suitable for describing the behavior of deformable bodies in elastic regime as well as in fracture phenomena. Indeed, different kind of fractures and post-fracture behaviors can be obtained by suitably varying the parameters of the model.

A further generalization of higher gradient continua is represented by the microstructured models, in which independent kinematical micro-descriptors are introduced. These models can be employed, in particular, for describing bone growth under cyclic loading and internal friction in the concrete. The former topic is investigated by means of a parametric analysis aiming to evaluate the sensitivity of the model to changes of some critical quantities within the physiological ranges. The latter topic is studied by means of a model in which the relative sliding between the faces of the microcracks inside the skeleton of the material is described by an independent kinematical descriptor. The addition of a micro-filler has relevant effects on the dissipation properties, as shown by both numerical and experimental data.

An important topic (often arising when investigating such complex systems) is the one of Hadamard stability of nonlinear elastic solids. New sufficient conditions are obtained by means of an approach, based on the Korn inequality, that is applied to determine an optimal lower bound estimate for the critical load. The effectiveness of the procedure, which is expandable to general cases of hyperelastic materials subject to inhomogeneous deformations, is discussed with reference to the cases of homogeneous uniaxial compression and triaxial extension-compression of a homogeneous, isotropic Mooney-Rivlin circular cylinder.

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