

TIME TABLE
registration on Monday at 8.30

TIME	Monday June 25	Tuesday June 26	Wednesday June 27	Thursday June 28	Friday June 29
9.00 - 9.45	Kerschen	Shaw	Shaw	Cochehin	Touze
9.45 - 10.30	Kerschen	Shaw	Shaw	Cochehin	Touze
11.00 - 11.45	Vakakis	Touze	Gendelman	Touze	Cochehin
11.45 - 12.30	Vakakis	Touze	Discussion	Touze	Cochehin
14.00 - 14.45	Shaw	Vakakis	Vakakis	Cochehin	
14.45 - 15.30	Shaw	Vakakis	Vakakis	Cochehin	
16.00 - 16.45	Gendelman	Kerschen	Gendelman	Kerschen	
16.45 - 17.30	Gendelman	Kerschen	Gendelman	Kerschen	

ADMISSION AND ACCOMMODATION

Applicants must contact CISM Secretariat at least one month before the beginning of the course. Application forms should be sent on-line through our web site: <http://www.cism.it> or by post.

A message of confirmation will be sent to accepted participants. If you need assistance for registration please contact our secretariat.

The 700,00 Euro registration fee includes a complimentary bag, four fixed menu buffet lunches (Friday not included), hot beverages, on-line/downloadable lecture notes and wi-fi internet access.

A limited number of participants from universities and research centres who are not supported by their own institutions can be offered board and/or lodging in a reasonably priced hotel. Requests should be sent to CISM Secretariat by **April 25, 2012** along with the applicant's curriculum and a letter of recommendation by the head of the department or a supervisor confirming that the institute cannot provide funding. Preference will be given to applicants from countries that sponsor CISM.

Information about travel and accommodation is available on our web site, or can be mailed upon request.

For further information please contact:

CISM
Palazzo del Torso
Piazza Garibaldi 18
33100 Udine (Italy)
tel. +39 0432 248511 (6 lines)
fax +39 0432 248550
e-mail: cism@cism.it

Centre International des Sciences Mécaniques
International Centre for Mechanical Sciences

ACADEMIC YEAR 2012
The Cercignani Session



**MODAL ANALYSIS OF NONLINEAR
MECHANICAL SYSTEMS**

Advanced School
coordinated by
Gaetan Kerschen
University of Liège
Belgium

Udine, June 25 - 29, 2012

MODAL ANALYSIS OF NONLINEAR MECHANICAL SYSTEMS

Modal analysis and testing of linear structures has been developed over the past 40-50 years, and the techniques available today are really quite sophisticated and advanced. Because nonlinearity is a frequent occurrence in real-life applications, there is a need for efficient nonlinear modal analysis methods. In this context, nonlinear normal modes (NNMs) offer a solid mathematical tool for interpreting a wide class of nonlinear dynamical phenomena, yet they have a clear conceptual relation to the classical linear normal modes (LNMs), with which structural engineers are familiar. However, for reasons that will be detailed during the course, most practicing engineers still view NNMs as a

concept that is foreign to them, and they do not yet consider them as a practical tool. This course will first introduce the concept of NNMs and their two main definitions. The undamped definition considers NNMs as a family of periodic orbits in the vicinity of an equilibrium point, whereas the damped definition, which is more general by essence, views an NNM as an invariant manifold in phase space. The fundamental differences between LNMs and NNMs will be highlighted (e.g., the frequency-energy dependence, bifurcations and modal interactions of NNMs) and illustrated using simple examples. The pedagogical treatment of NNMs will be

an important objective of the course so that the theory will be accessible to attendees coming from both academic and industrial areas. Different methods for computing NNMs from a mathematical model will be presented. Participants will be exposed to both advanced analytical and numerical methods. Particular attention will be devoted to the invariant manifold and normal form theories. We will also show that numerical algorithms pave the way for an efficient and practical computation of NNMs. Realizing that a large body of the literature deals with low-order lumped-mass models, complex structures including rotorcraft blades and a full-scale aircraft will be examined.

The course will also discuss experimental modal analysis, which amounts to extracting NNMs directly from experimental data. Two methods will be presented. The first method is based on the concept of slow flow and builds a model based on intrinsic modal oscillators. The second method relies on the generalization of the phase lag quadrature criterion to nonlinear systems. Advanced signal processing, including the wavelet transform, will prove very useful for experimental NNM identification. Finally, the course will describe several important applications of the NNM theory, including model validation, model reduction, and vibration and acoustic mitigation.

PRELIMINARY SUGGESTED READINGS

A.F. Vakakis, O. Gendelman, L.A. Bergman, D.M. McFarland, G. Kerschen, Y.S. Lee, *Nonlinear Targeted Energy Transfer in Mechanical and Structural Systems*, Springer, Berlin, 2008.

C. Pierre, D. Jiang, S. Shaw, *Nonlinear normal modes and their application in structural dynamics*, *Mathematical Problems in Engineering* (2006), 1-15.

C. Touze, M. Amabili, *Nonlinear normal modes for damped geometrically nonlinear systems: Application to reduced-order modeling of harmonically forced structures*, *Journal of Sound and Vibration* 298 (2006), 958-981.

G. Kerschen, M. Peeters, J.C. Golinval, A.F. Vakakis, *Nonlinear normal modes, Part I: A useful framework*

for the structural dynamicist, *Mechanical Systems and Signal Processing* 23 (2009), 170-194.

M. Peeters, R. Vigué, G. Sérandour, G. Kerschen, J.C. Golinval, *Nonlinear normal modes, Part II: Toward a practical computation using numerical continuation*, *Mechanical Systems and Signal Processing* 23 (2009), 195-216.

B. Cochelin, C. Vergez, *A high-order purely frequency-based harmonic balance formulation for continuation of periodic solutions*, *Journal of Sound and Vibration* 324 (2009), 243-262.

INVITED LECTURERS

Bruno Cochelin - Ecole Centrale de Marseille, France
6 lectures:
2 lectures on the harmonic balance method.
2 lectures on the asymptotic-numerical method.
2 lectures on acoustic mitigation.

Oleg Gendelman - Technion, Haifa, Israel
5 lectures:
2 lectures on slow invariant manifolds and nonlinear normal modes (NNMs).
1 lecture on the analysis of targeted energy transfer (TET).
2 lectures on TET and harmonic excitation.

Gaetan Kerschen - University of Liège, Belgium
6 lectures:
1 introductory lecture.
1 lecture on the definition and properties of NNMs.
2 lectures on the experimental identification of NNMs.
2 lectures on shooting and pseudo-arclength continuation.

Steve Shaw - Michigan State University, East Lansing, MI, USA
6 lectures:
1 lecture on the definition of damped NNMs.
1 lecture on the analytical computation of damped NNMs.
2 lectures on the numerical computation of NNMs.
2 lectures on NNM-based model reduction.

Cyril Touzé - Ecole Nationale Supérieure de Techniques Avancées, Palaiseau, France
6 lectures:
1 lecture on normal form theory.
1 lecture on normal form for vibratory systems.
1 lecture on normal form and invariant manifold.
1 lecture on hardening softening behavior of NNMs.
2 lectures on NNM-based model reduction.

Alexander Vakakis - University of Illinois at Urbana-Champaign, IL, USA
6 lectures:
2 lectures on NNMs and localization.
2 lectures on slow flows and system identification.
1 lecture on aeroelastic instability suppression.
1 lecture on shock and seismic mitigation.

LECTURES

All lectures will be given in English. Lecture notes can be downloaded from CISM web site, instructions will be sent to accepted participants.

**MODAL ANALYSIS
OF NONLINEAR MECHANICAL SYSTEMS**

Udine, June 25 - 29, 2012
Application Form
(Please print or type)

Surname _____

Name _____

Affiliation _____

Address _____

E-mail _____

Phone _____ Fax _____

Method of payment upon receipt of confirmation (Please check the box)

The fee of Euro 700,00 includes IVA/VAT tax and excludes bank charges

I shall send a check of Euro _____

Payment will be made to CISM - Bank Account N° 094570210900,
VENETO BANCA - Udine (CAB 12300 - ABI 05035 - SWIFT/BIC VEBHIT2M -
IBAN CODE IT46 N 05035 12300 09457 0210900).
Copy of the receipt should be sent to the secretariat

I shall pay at the registration counter with check, cash or VISA
Credit Card (Mastercard/Eurocard, Visa, CartaSi)

IMPORTANT: CISM is obliged to present an invoice for the above sum. Please indicate to whom the invoice should be addressed.

Name _____

Address _____

C.F.* _____

VAT/IVA* No. _____
(* Only for EU residents or foreigners with a permanent business activity in Italy.)

Only for Italian Public Companies

I ask for IVA exemption (ex law n. 537/1993 - art. 14 comma 10).

Privacy policy: I understand that data received via this form will be used only to provide information about CISM and its activities, within the limits set by the Italian legislative decree no. 196/2003 and subsequent amendments.

Complete information on CISM's privacy policy is available at http://www.cism.it/courses/privacy_statement/

I have read the "Admission and Accommodation" terms and conditions and agree.

Date _____ Signature _____

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