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Frid	July	Tis	Tis	Alle	May					
Thursday	July 26	Abrahamsson	Abrahamsson	Tiso	Allen	Tiso	Allen	Tiso	Allen	
Wednesday	July 25	Abrahamsson	Abrahamsson	Mayes	van der Seijs	Mayes	van der Seijs	van der Seijs	van der Seijs	
Tuesday	July 24	van der Seijs	Allen	Mayes	Rixen	Rixen	van der Seijs	Mayes	Mayes	
Monday	July 23	Registration	Rixen	Rixen	Rixen	Rixen	Tiso	Rixen	Rixen	Welcome Aperitif
TIME		9.00 - 9.45	9.45 - 10.30	11.00 - 11.45	11.45 - 12.30	14.00 - 14.45	14.45 - 15.30	16.00 - 16.45	16.45 - 17.30	18.00

**FIME TABLE** 

## ADMISSION AND ACCOMMODATION

The registration fee is 600.00 Euro + VAT\*, where applicable (bank charges are not included). The registration fee includes a complimentary bag, four fixed menu buffet lunches (on Friday upon request), hot beverages, downloadable lecture notes and wi-fi internet access.

**EAR 201** 

The Cowin Session

Centre International des Sciences Mécaniques International Centre for Mechanical Sciences

(CISM

Applicants must apply at least one month before the beginning of the course. Application forms should be sent on-line through the following web site: http://www.cism.it. A message of confirmation will be sent to accepted participants. Applicants requiring assistance with the registration should contact the secretariat at the following email address cism@cism.it.

Applicants may cancel their course registration and receive a full refund by notifying CISM Secretariat in writing (by email to cism@cism.it) no later than two weeks prior to the start of the course.

Cancellation requests received during the two weeks prior to the start of the course will be charged a 50.00 Euro handling fee. Incorrect payments are also subject to a 50.00 Euro handling fee.

A limited number of participants from universities and research centres who are not supported by their own institutions can be offered lodging and/or board, if available, in a reasonably priced hotel or student guest house.

Requests should be sent to CISM Secretariat by **May 23**, **2018** 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 the web site www.cism.it, or can be mailed upon request.

\* Italian VAT is 22%.

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 SUBSTRUCTURING IN ENGINEERING DYNAMICS: EMERGING NUMERICAL AND EXPERIMENTAL TECHNIQUES

Advanced School coordinated by

Matthew Allen University of Wisconsin-Madison USA

Daniel Rixen Technical University of Munich Germany

Udine July 23 - 27 2018

#### SUBSTRUCTURING IN ENGINEERING DYNAMICS: EMERGING NUMERICAL AND EXPERIMENTAL TECHNIQUES

One fundamental paradigm in engineering is to break a structure into simpler components in order to simplify test and analysis. In the numerical world this concept is the basis for Finite Element discretization and is also used in model reduction through substructuring. In experimental dynamics, substructuring approaches are commonly used (for instance for Transfer Path Analysis), although the subtleties involved are perhaps not always adequately appreciated. Recently there has been renewed interest in using measurements alone to create dynamic models for certain components and then assembling them with numerical models to predict the behavior of an assembly. Substructured models are also highly versatile; when one component is modified it can be readily assembled with the unchanged parts to predict

the global dynamical behavior. Substructuring concepts are critical to engineering practice in many disciplines, and they hold the potential to solve pressing problems in testing and modeling structures where nonlinearities cannot be neglected.

In this short course we will review a general framework which can be used to describe a multitude of methods and the fundamental concepts underlying substructuring. The course is aimed at explaining the main concepts as well as specific techniques needed to successfully apply substructuring both numerically (i.e. using finite element models) and experimentally. Therefore, handson exercises will be included to illustrate the concepts using routines written in Matlab® and real-life applications will be presented. The course is centered around the

following topics, which range from classical substructuring methods to topics of current research such as substructuring for nonlinear systems.

1.Primal and dual assembly of structures and applications to parallel computing. 2.Model reduction and substructuring for linear systems including Guyan and Hurty/Craig-Bamtpon reduction. McNeal. Rubin, Craig-Chang, etc... Recently developed interface reduction methods will also be reviewed. 3. Experimental-Analytical substructuring including modal substructuring methods such as the transmission simulator method and frequency domain methods such as impedance coupling. 4. Model reduction and substructuring methods for nonlinear systems: Overview of traditional nonlinear FEA including geometric nonlinearity. Nonlinear

Normal Modes and other analytical techniques for nonlinear systems will be reviewed to demystify nonlinearity and its effect on structural response. The special case of weakly nonlinear systems will also be treated including experimental identification methods and experimental substructuring.

The course is designed to provide practicing engineers or researchers such as PhD students with a firm grasp of the fundamentals as well as a thorough review of current research in emerging areas. Attendees are expected to have a solid foundation in structural dynamics and some exposure to finite element analysis. The course material will be of interest to those who primarily perform finite element simulations of dynamic structures, to those who primarily focus on modal test, and to those who work at the interface between test and analysis.

# PRELIMINARY SUGGESTED READINGS

D. de Klerk, D. J. Rixen, and S. N. Voormeeren, "General framework for dynamic substructuring: History, review, and classification of techniques," AIAA Journal, vol. 46, pp. 1169-1181, 2008, http://dx.doi. org/10.2514/1.33274.

M. V. Van Der Seijs, D. De Klerk, and D. J. Rixen, "General framework for transfer path analysis: History, theory and classification of techniques," Mechanical Systems and Signal Processing, vol. 68-69, pp. 217-244, 2016, http://dx.doi. org/10.1016/j.ymssp.2015.08.004. M. S. Allen, R. L. Mayes, and E. J. Bergman, "Experimental Modal Substructuring to Couple and Uncouple Substructures with Flexible Fixtures and Multi-point Connections," Journal of Sound and Vibration, vol. 329, pp. 4891–4906, 2010, http://dx.doi.org/10.1016/j. jsv.2010.06.007.

D. Krattiger, L. Wu, M. Zacharczuk, M. Buck, R. J. Kuether, M. S. Allen, P. Tiso, and M. R. W. Brake, "Interface Reduction for Hurty/ Craig-Bampton Substructured Models: Review and Improvement," Mechanical Systems and Signal Processing, vol. Submitted April., 2017.

R. J. Kuether, M. S. Allen, and J. J. Hollkamp, "Modal Substructuring for Geometrically Nonlinear Finite Element Models," AIAA Journal, vol. 54, pp. 691-702, 2016, http:// dx.doi.org/10.2514/1.J054036.

F. Gruber and D.J. Rixen. "Evaluation of substructure reduction techniques with fixed and free interfaces." Strojniški vestnik-Journal of Mechanical Engineering, vol. 62.7-8, pp. 452-462, 2016, http://dx.doi.org/10.5545/svjme.2016.3735.

Sjövall, Per, and Thomas Abrahamsson. "Substructure system identification from coupled system test data." Mechanical Systems and Signal Processing 22.1 (2008): 15-33.

L. Wu, P. Tiso, Nonlinear Model Order Reduction for Flexible Multibody Dynamics: a Modal Derivatives Approach, Multibody System Dynamics, Vol. 36 (4), 405-425, 2016.

## **INVITED LECTURERS**

Thomas Abrahamsson - Chalmers University, Gothenburg, Sweden

*4 lectures on:* State space substructuring, Finite Element Model Updating, industrial applications.

**Matthew S. Allen** - University of Wisconsin-Madison, USA *6 lectures on:* Experimental-analytical substructuring and the transmission simulator method, nonlinear normal modes, reduced order modeling and substructuring for nonlinear systems.

**Randall L. Mayes** - Sandia National Labs, Albuquerque, USA *6 lectures on: Transmission simulator method, experimentally derived models and modal test for substructuring.* 

**Daniel Rixen** - Technische Universität München, Germany *8 lectures on:* General framework for substructuring, numerical substructuring techniques & experimental substructuring such as frequency based substructuring techniques.

Paolo Tiso - ETH Zurich, Switzerland

*6 lectures on:* Analytical substructuring methods, interface reduction, model reduction methods for geometrically nonlinear finite element models.

**Maarten van der Seijs** - Co-founder of VIBES Technology, Delft, The Netherlands *6 lectures on:* Transfer path analysis, force reconstruction and industrial applications.

## LECTURES

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