Nonlinear Structural Dynamics
- The Fundamentals Tutorial
*Monday, February 2, 2015 | Session 1*

**Presented by:**
D.E. Adams, Vanderbilt University

Nonlinear behaviors abound in structural systems, and are challenging to identify and predict. Natural frequencies, damping levels, mode shapes, and amplitudes of response can all change unexpectedly and suddenly when nonlinear behaviors arise. How can we model and predict these kinds of behaviors? How can we design tests to observe such behavior? How do we adapt the tools of modal analysis to address engineering challenges posed by nonlinear structural dynamic behavior? This tutorial uses case studies to introduce tools and methods that can be used to address nonlinear dynamic behavior in vibration modeling and testing. Case studies are drawn from a wide range of aerospace and automotive applications involving advanced materials, components, and structural assemblies. Physical demonstrations are used to reinforce theoretical concepts and questions/discussion are encouraged.

Tutorial on Nonlinear Modal Analysis
*Wednesday, February 4, 2015 | Session 31*

**Presented by:**
G. Kerschen, University of Liège

Because nonlinearity is a frequent occurrence in real-life applications, there is a need for efficient theoretical and experimental nonlinear modal analysis methodologies. 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 and simple conceptual relation to the classical linear normal modes, with which practicing engineers are familiar. However, most structural engineers still view NNMs as a concept that is foreign to them. The objective of this tutorial is to introduce the concept of NNMs and to illustrate in a simple manner their fundamental properties. The usefulness of NNMs for theoretical and experimental modal analysis of nonlinear vibrating structures is then discussed and illustrated using academic and real-life examples.
In several engineering applications, structural nonlinearities cannot be avoided. In others, nonlinearities are exploited to enhance the structural performances. In both cases, accurate and efficient models are required to accurately predict the static and dynamic behavior of the system at hand.

Among different sources of nonlinearities, geometrical effects arise from large deflections that essentially redirect the internal stresses. They lead to structural static and dynamic behavior, which is qualitatively very different from their linear counterpart, with profound implications on the functioning, stability and strength of the structure.

This tutorial mainly focuses on the modelling and the simulation of static and dynamic structural systems characterized by geometric nonlinearities. Other relevant nonlinear effects are also briefly mentioned.

The following aspects will be discussed:

- Overview of typical geometric nonlinearity phenomena
- Kinematic modeling: exact vs. approximated models
- Finite element discretization: Lagrangian vs Corotational approach
- Solution techniques: Newton-Raphson, continuation methods, numerical time integration, implicit vs explicit schemes
- Model Order Reduction strategies

Several examples will be shown to support the theory. A basic knowledge of engineering dynamics, modal approximation and finite element analysis is assumed.
Acoustic fluid-structure interaction is a common issue in automotive applications. An example is the pressure-induced structure-borne sound of piping and exhaust systems. Efficient model order reduction and substructuring techniques accelerate the finite element analysis and enable the vibro-acoustic optimization of such complex systems with acoustic fluid-structure interaction. This tutorial reviews the application of the Craig-Bampton and the Rubin method to fluid-structure coupled systems and presents two automotive applications.

First, a fluid-filled brake-pipe system is assembled by substructures according to the Craig-Bampton method. Fluid and structural partitions are fully coupled in order to capture the interaction between the pipe shell and the heavy fluid inside the pipe. Second, a rear muffler with an air-borne excitation is analyzed. Here, the Rubin and the Craig-Bampton method are used to separately compute the uncoupled component modes of both the acoustic and structural domain. These modes are then used to compute a reduced model which incorporates full acoustic-structure coupling. For both applications, transfer functions are computed and compared to the results of dynamic measurements.

The vibro-acoustic behavior of ship-like structures is noticeably influenced by the surrounding water and thus represents a multi-field problem. In this tutorial, fast boundary element methods are applied for the semi-infinite fluid domain. As an advantage, the Sommerfeld radiation condition is satisfied in an exact way and only the boundary, i.e. the ship hull, has to be discretized. To overcome the draw-back of fully populated matrices, fast boundary element methods are applied. The focus is on the comparison of the multipole method with hierarchical matrices, which are set up by adaptive cross approximation. In both cases, a half-space fundamental solution is used to incorporate the water surface, which is treated as pressure-free. The structural domain is discretized with the finite element method. A binary interface to the commercial finite element package ANSYS is used to import the mass and stiffness matrices. The coupled problems are formulated as Schur complements, which are solved by a combination of iterative and direct solvers. Depending on the applied fast boundary element method, different strategies arise for the preconditioning and the overall solution. The applicability of these approaches is demonstrated using a realistic model problem.
The tutorial starts off with the notion of damping and the causes of damping before dealing with different modelling approaches for the linear and nonlinear behaviour of solids. Linear viscoelastic materials are discussed in great detail. They are followed by the damping of assemblies, relevant to the user, by its mathematical characterisation and its relation to material damping. Models for damped structures are discussed next, and the application of the Finite Element Method (FEM) and the Boundary Element Method (BEM) is explained. Finally, as statements on damping rely on experiments, Part 5 describes established experimental techniques, possible instrumentation for the determination of damping characteristics.