Tutorial Guideline VDI 3830: Damping of Materials and Members

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Committee Background

It was Nov 10, 1982 when Prof. Federn, Prof. Gaul, Prof. Mahrenholtz, and Dr. Pieper VDI decided to work out a guideline on damping in the VDI/FANAK C13 Committee "Material Damping". They were joined by Prof. Ottl, Prof. Kraemer, Prof. Pfeiffer, Prof. Markert, Prof. Wallaschek, and Mr. Hilpert VDI lateron in their names order. The idea was to comprise distributed theoretical and experimental knowledge and to homogenize the nomenclature of this subject.

At the very beginning, important knowledge was provided by the books

J.D. Ferry: Viscoelastic Properties of Polymers
John Wiley & Sons, New York, 1960
B.J. Lazan: Damping of Matrials and Members in Structural Mechanics
Pergamon Press, Oxford, 1968

Important contributions to the subject were made at conferences in the USA, such as

– Damping
  Lynn Rogers
– The Role of Damping in Vibration and Noise Control, ASME Boston
  Lynn Rogers, Lothar Gaul
– Damping Sessions at IMAC
  Lothar Gaul et al

and in Germany by the colloquium

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T. Proulx (ed.), *Modal Analysis Topics, Volume 3*, Conference Proceedings of the Society for Experimental Mechanics Series 6,
DOI 10.1007/978-1-4419-9299-4_2, © The Society for Experimental Mechanics, Inc. 2011

- Daempfungsverhalten von Werkstoffen und Bauteilen
  Kolloquium, TU Berlin, 1975 VDI-GKE
  H. Fuhrke, K. Federn, R. Gasch

Results of five guidelines worked out by the named committee

VDI-Richtlinie 3830, Blatt 1-5

have been presented at the conference

Schwingungsdaempfung (Vibration Damping)
October 16 and 17, 2007, Wiesloch near Heidelberg

providing information about

- modelling
- numerical methods (Finite Elements, Boundary Elements, Modal Analysis)
- experimental techniques for determining material damping properties from measured components or system characteristics

along with

- passive and adaptive practical applications.

The guideline VDI 3830 "Damping of Materials and Members"

The guideline VDI 3830 consists of the following parts:

Part 1 Classification and survey

Part 2 Damping of solids
Preliminary note
1 Physical phenomena
2 Linear models
3 Nonlinear models

Part 3 Damping of assemblies
Preliminary note
1 From the material to the homogeneous member
2 Laminated members
3 Damping in joints
4 Damping due to fluids
5 Damping by squeezing
6 Assemblies

Part 4 Models for damped structures
Preliminary note
1 Basic model
2 Structures with finite number of degrees of freedom
3 Calculation of viscoelastic components using the boundary element method

Introduction

All dynamic processes in mechanical systems are more or less damped. Consequently, damping is highly relevant in those fields of technology and applied physics which deal with dynamics and vibrations. These include

- machine-, building-, and structural dynamics,
- system dynamics,
- control engineering, and
- technical acoustics,

because damping in these cases often has a considerable effect on the time history, intensity, or even the existence of vibrations. Important applications are:

- transient vibrations (transient effects associated with the onset or decay of vibrations, shock-induced vibrations, reverberation effects)
- resonance vibrations (unavoidable with random excitation)
- wave propagation
- dynamic-stability problems

Accordingly, a multitude of scientific publications dealing with damping, or taking it into account at least, are found in technical literature. Due to different theory approaches, objects, and task definitions in the applications listed above, the designations, the characterisation of damping, the experimental techniques, and the analytical and numerical methods are not harmonised.

The dynamic behaviour of damped structures can, in special cases, be calculated using generally valid material laws for inelastic materials based on continuum mechanics taking into account boundary effects (e.g. joints). In general, this approach is too elaborate or expensive, or not at all practicable. In most cases, therefore, phenomenological equivalent systems or mathematical models tailored to the task definition are used which are only valid assuming a special state of stresses and/or a special time history. Harmonic (sinusoidal) time histories are a preferred special case where complex quantities describe the elastic and damping properties. These depend on a number of parameters: material data, rate of deformation, frequency, temperature, number of load cycles, etc. In the case of nonlinear behaviour there is also a dependence on the amplitude.

For certain problems, it is sufficient to state, for one deformation cycle, the energy dissipated in a unit volume or within the system, or the energy released into the environment at the system boundaries, often related to a conveniently chosen elastic energy in a unit volume or in the system as a whole. In structural dynamics, the use of modal damping ratios has proven useful, which do no longer contain detailed information about the damping.

This guideline is not a textbook; it cannot be a compilation of generally mandatory rules. It is intended

- to contribute to a better understanding of the physical causes of damping,
- to facilitate interdisciplinary cooperation by defining harmonised terms and pointing out the relations between different approaches to the modelling of damping, and
- to allow an overview of the state of knowledge and experience gathered in various fields of application and research,

in order to promote the application of existing knowledge.

This guideline is structured in accordance with its objective. It 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, and establishing cross-references between these approaches. Linear viscoelastic materials being the best investigated. Their behaviour is 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 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, and analytical methods.

The notion of damping

Damping in mechanical systems is understood to be the irreversible transition of mechanical energy into other forms of energy as found in time-dependent processes. Damping is mostly associated with the change of mechanical energy into thermal energy. Damping can also be caused by releasing energy into a surrounding medium. Electromagnetic and piezoelectric energy conversion can also give rise to damping if the energy converted is not returned to the mechanical system.

Classification of damping phenomena

The physical causes of damping are multifarious. In addition to friction, wave propagation or flow effects, other possible causes are phase transitions in materials or energy conversion by piezoelectric, magnetostrictive, or electromechanical processes.

Forces associated with damping are non-conservative. They can be internal or external forces. If both action and reaction forces in a free body diagram the damping force, are effective within the system boundaries, the effect is said to be an internal damping effect. Where the reaction force is effective outside the system boundaries, the effect is an external damping effect.

Examples of internal damping are:

- material damping due to nonelastic material behaviour
- friction between components, e.g. in slide ways, gears, etc.
- conversion of mechanical vibration energy into electrical energy by means of the piezoelectric effect and dissipation due to dielectric losses

Examples of external damping are:

- friction against the surrounding medium
- air-borne-sound radiation into the environment
- structure-borne-sound radiation into the ground

Phenomenologically, the damping in a mechanical system can be composed of the following contributions:

- *Material damping*
  The energy dissipation within a material, due to deformation and/or displacement, is called material damping. Its physical causes are, in essence:
  - in solids
    - heat flows induced by deformation (thermomechanical coupling)
    - slip effects
    - microplastic deformations
    - diffusion processes
  - in fluids
    - viscous flow losses
- *Contact-surface damping*
  Relative motion, friction
  Contact-surface damping is caused by relative motions in the contact surfaces of joined components such as screwed, riveted, and clamped joints. The physical causes are:
  - friction due to relative motions in the contact surface
  - pumping losses in the enclosed medium due to relative motion in a direction normal to the contact surface (e.g. gas pumping)

  The term “structural damping” includes:

- Damping in guides
  This includes energy dissipation in longitudinal guides (e.g. slides) and circular guides (e.g. journal bearings).
- Electromechanical damping
  Electromechanical damping can be caused by piezoelectric, magnetostrictive, or electromagnetic effects.
- Energy release to the surrounding medium
  This includes:
  - air damping
  - fluid damping
  - bedding damping

Notes on modern, computer-based analytical and measurement programs

Whereas the mass and stiffness matrices of relatively complex structures can be readily determined nowadays using three-dimensional CAD drawings, automatic grid generation, and subsequent FEM analysis, an appropriate calculation model cannot usually be established which sufficiently precise information on damping. More precise damping parameters contains can be determined experimentally.

"Experimental Modal Analysis" (EMA) has become established as the suitable tool worldwide. It uses measured frequency-response curves between appropriately chosen excitation points and measuring points, and modern curve-fitting techniques for identifying the modal parameters: natural frequencies, eigenmodes, and modal damping ratios. In the case of simple structures, the system can be excited by means of a hammer inpact. In the case of complex components and considerable damping, excitation using one or several exciters has proven convenient, allowing to control exciter amplitudes and energy distribution for selected frequency ranges. The system response is often measured by means of piezoelectric accelerometers or laser-optical sensors.

Modern measurement and analytical systems offer the possibility to identify discrete damping couplings provided that the substructures have been separately investigated beforehand.

Link modules allow to establish the connection between the results of experimental modal analysis and the calculated FEM analysis (e.g. matching of nodal points and coordinate axes through interpolation). Quality criteria such as MAC (Modal Assurance Criterion) compare the relations (such as orthogonality) between the eigenmodes found in terms of the scalar product of the eigenvectors. Additional normalisation using the mass or stiffness matrix allows a quantitative assessment.

After model updating on the modal level, including damping ratios determined by experiment, operation vibrations can be calculated for any load function. The simulation model which was developed step by step can thus be verified under practical conditions.

Content of tutorial

The content of the guideline VDI 3830 is explained in the tutorial along with physics, theory, numerical approaches, and practical applications taken from review articles and archival publications of the tutor and his coworkers focussed on damping topics.

1. L. Gaul: The Influence of Damping on Waves and Vibrations
   Mechanical Systems and Signal Processing (1999) 13(1), 1-30
   Wave propagations and vibrations are associated with the removal of energy by dissipation or radiation. In mechanical systems damping forces causing dissipation are often small compared to restoring and inertia forces, However, their influence can be great and is discussed in the present survey paper together with the transmission of energy away from the system by radiation. Viscoelastic constitutive equations with integer and fractional time derivatives for the description of stress relaxation and creep of strain as well as for the description of stress-strain damping hysteresis under cyclic oscillations are compared. Semi-analytical solutions of wave propagation and transient vibration problems are obtained by integral transformation and elastic-viscoelastic correspondence principle. The numerical solution of boundary value problems requires discretization methods. Generalized damping descriptions are incorporated in frequency and time domain formulations for the boundary element method and the finite element method.
2. L. Gaul and R. Nitsche: The Role of Friction in Mechanical Joints
   Appl Mech Rev vol 54, no 2, March 2001, 93-109
   Vibration properties of most assembled mechanical systems depend on frictional damping in joints. The nonlinear transfer behavior of the frictional interfaces often provides the dominant damping mechanism in a built-up structure and plays an important role in the vibratory response of the structure. For improving the performance of systems, many studies have been carried out to predict, measure, and/or enhance the energy dissipation of friction. This article reviews approaches for describing the nonlinear transfer behavior of bolted joint connections. It gives an overview of modeling issues. The models include classical and practical engineering models. Constitutive and phenomenological friction models describing the nonlinear transfer behavior of joints are discussed. The models deal with the inherent nonlinearity of contact forces (e. g. Hertzian contact), and the nonlinear relationship between friction and relative velocity in the friction interface. The research activities in this area are a combination of theoretical, numerical, and experimental investigations. Various solution techniques, commonly applied to friction- damped systems, are presented and discussed. Recent applications are outlined with regard to the use of joints as semi-active damping devices for

vibration control. Several application areas for friction damped systems due to mechanical joints and connections like shells and beams with friction boundaries are presented. This review article includes 134 references.

3. A. Schmidt and L. Gaul: Finite Element Formulation of Viscoelastic Constitutive Equations Using Fractional Time Derivatives
Nonlinear Dynamics 29, 37-55, 2002
Fractional time derivatives are used to deduce a generalization of viscoelastic constitutive equations of differential operator type. These so-called fractional constitutive equations result in improved curve-fitting properties, especially when experimental data from long time intervals or spanning several frequency decades need to be fitted. Compared to integer-order time derivative concepts less parameters are required. In addition, fractional constitutive equations lead to causal behavior and the concept of fractional derivatives can be physically justified providing a foundation of fractional constitutive equations. First, three-dimensional fractional constitutive equations based on the Grünwaldian formulation are derived and their implementation into an elastic FE code is demonstrated. Then, parameter identifications for the fractional 3-parameter model in the time domain as well as in the frequency domain are carried out and compared to integerorder derivative constitutive equations. As a result the improved performance of fractional constitutive equations becomes obvious. Finally, the identified material model is used to perform an FE time stepping analysis of a viscoelastic structure.
4. L. Gaul and M. Schanz: A comparative study of three boundary element approaches to calculate the transient response of viscoelastic solids with unbounded domains
Comput. Methods Appl. Mech. Engrg. 179 (1999), 111-123
As an alternative to domain discretization methods, the boundary element method (BEM) provides a powerful tool for the calculation of dynamic structural response in frequency and time domain. Field equations of motion and boundary conditions are cast into boundary integral equations (BIE), which are discretized only on the boundary. Fundamental solutions are used as weighting functions in the BIE which fulfil the Sommerfeld radiation condition, i.e., the energy radiation into a surrounding medium is modelled correctly. Therefore, infinite and semi-infinite domains can be effectively treated by the method. The soil represents such a semi-infinite domain in soil-structure-interaction problems. The response to vibratory loads superimposed to static pre-loads can often be calculated by linear viscoelastic constitutive equations. Conventional viscoelastic constitutive equations can be generalized by taking fractional order time derivatives into account. In the present paper two time domain BEM approaches including generalized viscoelastic behaviour are compared with the Laplace domain BEM approach and subsequent numerical inverse transformation. One of the presented time domain approaches uses an analytical integration of the elastodynamic BIE in a time step. Viscoelastic constitutive properties are introduced after Laplace transformation by means of an elasticviscoelastic correspondence principle. The transient response is obtained by inverse transformation in each

time step. The other time domain approach is based on the so-called 'convolution quadrature method'. In this formulation, the convolution integral in the BIE is numerically approximated by a quadrature formula whose weights are determined by the same Laplace transformed fundamental solutions used in the first method and a linear multistep method. A numerical study of wave propagation problems in 3-d viscoelastic continuum is performed for comparing the three BEM formulations.

5. L. Gaul, H. Albrecht and J. Wirnitzer: Semi-active friction damping of large space truss structures
   Shock and Vibration 11 (2004), 173-186
   The authors dedicate this paper to the memory of Professor Bruno Piombo. We commemorate him as a vital contributor to our science. From the experience of sharing conferences and workshops with Bruno since many years, learning from his expertise and appreciating his advice, the first author mourns the loss of a good friend whose works and words will be kept in our minds and hearts.
   The present approach for vibration suppression of flexible structures is based on friction damping in semi-active joints. At optimal locations conventional rigid connections of a large truss structure are replaced by semi-active friction joints. Two different concepts for the control of the normal forces in the friction interfaces are implemented. In the first approach each semi-active joint has its own local feedback controller, whereas the second concept uses a global, clipped-optimal controller. Simulation results of a 10-bay truss structure show the potential of the proposed semi-active concept.

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