Frequency detuning effects for a parametric amplifier

Frequency tuned parametric amplifiers may experience changes in both the two-to-one frequency ratio between the parametric and the direct excitation, and between the direct excitation frequency and the system's natural frequency. These effects are investigated theoretically using a Duffing-Mathieu equation as the model system, and investigated experimentally using a macro cantilever beam as the model object. The approximate analytical steady-state vibration amplitudes are derived using the method of varying amplitudes, and compared with results of direct numerical integration, showing good agreement. Theoretical predictions reveal that for detuned superthreshold parametric amplification some of the amplitude-frequency curves appear to collapse. Experiments show that a drop in the maximum steady-state vibration amplitude occurs for specific areas in the amplitude-excitation detuning domain, whereas for other areas frequency detuning may yield an increased maximum steady-state vibration amplitude. Thus frequency detuning is a feature which can purposefully be avoided or utilized, dependent on the usage e.g. for sensors or energy harvesters. We report experimentally obtained bistable amplified steady-state responses, which also support theoretical findings.

General information
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering, Eindhoven University of Technology
Contributors: Neumeyer, S., Sorokin, V., van Gastel, M. H. M., Thomsen, J. J.
Pages: 77-87
Publication date: 2019
Peer-reviewed: Yes

Publication information
Journal: Journal of Sound and Vibration
Volume: 445
ISSN (Print): 0022-460X
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
Original language: English
Keywords: Parametric amplification, Frequency detuning, Nonlinearity
DOIs:
10.1016/j.jsv.2018.12.036
Source: FindIt
Source-ID: 2442889484
Research output: Contribution to journal › Journal article – Annual report year: 2019 › Research › peer-review

Transverse vibrations induced by longitudinal excitation in beams with geometrical and loading imperfections

With structural health monitoring techniques based on measuring transverse vibrations of beam-like components it can be difficult to provide transverse excitation, while longitudinal excitation can be easier. We experimentally investigate how transverse vibrations in a beam can be excited by a longitudinal hammer impact. We carry out a comparative study on the measured transverse natural frequencies and frequency response coherence for different input and output locations and directions. It is shown that transverse vibrations are excited regardless of the impact locations and directions. Theoretical explanation to this counter-intuitive phenomenon is provided in terms of various imperfections associated with beams and impacts.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics, Brüel and Kjær Sound and Vibration Measurement A/S, Technical University of Denmark
Contributors: Sah, S. M., Thomsen, J. J., Tcherniak, D.
Pages: 152-160
Publication date: 2019
Peer-reviewed: Yes

Publication information
Journal: Journal of Sound and Vibration
Volume: 444
ISSN (Print): 0022-460X
Ratings:
BFI (2019): BFI-level 2
Web of Science (2019): Indexed yes
Original language: English
Keywords: Beam imperfection, Impact imperfection, Longitudinal impact, Transverse vibrations
Unilateral Vibro-Impact Systems—Experimental Observations against Theoretical Predictions based on the Coefficient of Restitution

The vibro-impact response of a single-degree of freedom model with the coefficient of restitution is analyzed using pointwise mapping and a standard averaging combined with non-smooth transformations. Experimental data are taken from a cantilever beam with attached mass and unilateral constraint submitted to different gap configurations and levels of excitation. Numerical simulations are used to reproduce empirical observations to a certain extent and validate theoretical predictions. Investigations on the coefficient of restitution show its dependence on the forcing frequency and pre-contact velocity. The effect of gap variations due to sliding of the constraint during frequency sweep is analyzed experimentally.

Estimating bolt tightness from measured vibrations: Influence of boundary nonlinearity

A technique is proposed to assess the level of bolt tightness and to quantify the tension based on measured natural frequencies and damping ratios of the bolt. This technique is investigated experimentally and theoretically. A simple model for the bolt that consists of a pre-stressed one dimensional beam linear equation with nonlinear stiffness and damping at its boundaries is investigated to explain experimental results. Figure 1a shows the squared first bending natural frequency for a bolt as function of bolt tension. At low tension the squared natural frequency rapidly increases with tension. As the bolt is gradually tightened the frequency starts changing approximately linearly with tension [1, 2]. Figure 1b shows the first mode damping ratio of the bolt as function of the bolt tension. At low tension the damping ratio decreases rapidly with tension and then starts slowly decreasing for higher tension.
Estimating bolt tightness from measured vibrations: Influence of nonlinear boundary stiffness and damping

In this work we present a technique to assess the level of bolt tightness and to quantify the tension based on measured natural frequencies and damping ratios of the bolt. This technique is investigated experimentally and theoretically. A simple model for the bolt that consists of a pre-stressed one-dimensional beam linear equation with linear and nonlinear stiffness and damping at its boundaries is investigated to explain experimental results. Figure 1a shows the squared first bending natural frequency for a bolt as function of bolt tension. At low tension the squared natural frequency rapidly increases with tension. As the bolt is gradually tightened the squared frequency starts changing approximately linearly with tension [1]. Figure 1b shows the first mode damping ratio of the bolt as function of the bolt tension. At low tension the damping ratio decreases rapidly with tension and then starts slowly decreasing for higher tension. A mathematical beam model with linear/nonlinear stiffness and damping at its boundaries is used to explain the experimental results.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics, Karlsruhe Institute of Technology, Brüel and Kjær Sound and Vibration Measurement A/S
Contributors: Sah, S. M., Thomsen, J. J., Brøns, M., Fidlin, A., Tcherniak, D.
Number of pages: 1
Publication date: 2018
Peer-reviewed: Yes
Event: Abstract from International Conference on Structural Nonlinear Dynamics and Diagnosis (CSNDD'2018), Tangier, Morocco.

Research output: Contribution to conference › Conference abstract for conference – Annual report year: 2018 › Research › peer-review

Estimating bolt tightness using transverse natural frequencies

Structural health monitoring techniques based on vibration measurements have been receiving large attention in the last decades, including techniques for estimating bolted joint tightness and detecting loosened bolts. Due to the exposure of bolted joints to external forces, the bolts may loosen and therefore affect healthy functioning of the bolted structure. In this work a technique is proposed to estimate the level of bolt tightness and to quantify the tension based on the measured natural frequencies of the bolt, in particular the first transverse natural frequency. An experiment is performed on two structure specimens each clamped with a bolt of different length. The bolts bending vibrations are excited by impacting the bolts head along the transverse direction. The excited transverse natural frequencies are then recorded as the bolts are gradually tightened. The measured frequencies trends are explained by modeling the bolt as a pre-stressed one dimensional beam with elastic supports at both ends. The experimental results are reproduced using an analytical function that expresses the boundaries stiffness in terms of the bolt tension. The sensitivity of the measured bolt first transverse natural frequency demonstrates the potential of this frequency-based technique in estimating bolt tightness.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics, Technical University of Denmark, Karlsruhe Institute of Technology, Brüel and Kjær Sound and Vibration Measurement A/S
Contributors: Sah, S. M., Thomsen, J. J., Brøns, M., Fidlin, A., Tcherniak, D.
Pages: 137-149
Publication date: 2018
Peer-reviewed: Yes

Publication information
Journal: Journal of Sound and Vibration
Volume: 431
ISSN (Print): 0022-460X
Ratings:
BFI (2018): BFI-level 2
Web of Science (2018): Indexed yes
Original language: English
Keywords: Bolt, Boundary stiffness, Hammer impact, Natural frequency, Tightness, Transverse vibration
DOIs: 10.1016/j.jsv.2018.05.040
Source: Scopus
Source-ID: 85048093170
Research output: Contribution to journal › Journal article – Annual report year: 2018 › Research › peer-review
Modal impact testing for estimating bolted joint tightness

The tension level in a bolt is difficult to determine and control. Based on simple hammer impacts, a novel technique is proposed to quantify the level of bolt tightness by analyzing natural frequencies and damping ratios of the bolt. The technique is investigated experimentally by testing two different bolts (short and long) and measuring accelerations in the transverse directions. At low tension the squared natural frequency of the first bending mode increases strongly with tension. As the bolt is gradually tightened, the squared frequency starts changing more weakly and approximately linearly with tension. By signal processing the transient response from the hammer impact, and treating problems of beat-frequencies due to the near cross sectional symmetry in the bolt, the corresponding effective linear damping ratios can also be obtained. Further, a scanning laser Doppler vibrometer (SLDV) is used to measure the mode shapes of the long bolt and it is studied how these change with tension.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics, Karlsruhe Institute of Technology, Brüel and Kjær Sound and Vibration Measurement A/S
Contributors: Brøns, M., Thomsen, J. J., Fidlin, A., Tcherniak, D., Sah, S. M.
Number of pages: 8
Publication date: 2018

On the feasibility of utilizing vibrations for bolted joint assessment
For many technical installations held together by bolted joints, the regular checking and documentation of proper bolt tightness is essential for certification and safe operation. With large structures and heavy bolts, this requires long hours of monotonous and physically demanding physical work, possibly in tough environments. A better way of monitoring bolt tightness is on high demand in many industries.

The presented study is based on recent experimental results and theoretical studies that indicate and explain the correlation between transient bolt vibrations due to e.g. a hammer impact and bolt tension. The study presents an overview of the features that can be extracted from measured vibrational response and can characterize bolt tension. The main objective of the study is to discuss the practical applicability of these features to robust detection of loosen bolts and a feasibility of a relatively simple and not demanding vibration-based system to monitor bolt tension in industrial environments.

General information
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering, Brüel and Kjær Sound and Vibration Measurement A/S
Contributors: Tcherniak, D., Thomsen, J. J.
Number of pages: 10
Publication date: 2018
Peer-reviewed: Yes
Event: Paper presented at 9th European Workshop on Structural Health Monitoring (EWSHM 2018), Manchester, United Kingdom.
Source: PublicationPreSubmission
Source-ID: 153558327
Research output: Contribution to conference › Paper – Annual report year: 2018 › Research › peer-review

Vibration-based estimation of beam boundary parameters
Two methods are suggested for using measured vibrations to estimate linear boundary stiffness and damping for beams, while simultaneously estimating axial tension. Estimation is performed by fitting model boundary parameters to measured modal vibration data. The methods are validated using simulated and experimental data, and shown to be accurate when boundary parameters are not extreme, i.e. representing either zero stiffness or compliance.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Technical University of Denmark
Corresponding author: Thomsen, J. J.
Contributors: Hermansen, M. B., Thomsen, J. J.
Pages: 287-304
Experimental validation of vibro-impact force models using numeric simulation and perturbation methods

The frequency response of a single-degree of freedom vibro-impact oscillator is analysed using Harmonic Linearization, Averaging and Numeric Simulations considering two different impact force models, one given by a piecewise-linear function and other by a high-order polynomial. Experimental validation is carried out using control-based continuation to obtain the experimental frequency response, including its unstable branch.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: de Souza Reboucas, G. F., Santos, I., Thomsen, J. J.
Pages: 2
Publication date: 2017

Host publication information
Title of host publication: Proceedings of the 9th European Nonlinear Dynamics Conference
Publisher: CongressLine Ltd.
Editors: Stépán, G., Csernák, G.
ISBN (Electronic): 978-963-12-9168-1
Electronic versions:
ConferencePresentation_2017_1.pdf
Source: PublicationPreSubmission
Source-ID: 139847501

Validation of Vibro-Impact Force Models by Numerical Simulation, Perturbation Methods and Experiments

The frequency response of a single degree of freedom vibro-impact oscillator is analyzed using Harmonic Linearization, Averaging and Numeric Simulation, considering three different impact force models: one given by a piecewise-linear function (Kelvin-Voigt model), another by a high-order power function, and a third one combining the advantages of the other two. Experimental validation is carried out using control-based continuation to obtain the experimental frequency response, including its unstable branch.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: de Souza Reboucas, G. F., Santos, I., Thomsen, J. J.
Pages: 291–307
Publication date: 2017
Peer-reviewed: Yes

Publication information
Journal: Journal of Sound and Vibration
Volume: 413
ISSN (Print): 0022-460X
Ratings:
BFI (2017): BFI-level 2
Vibration-based testing of bolted joints

In recent pilot studies we have started investigating how to possibly use measured flexural (i.e. transverse/bending) vibrations, induced by bolt-tapping, to estimate bolt tightness. Some of the vibration features we investigated showed strong correlation with bolt tightness. For example, the lowest natural frequency, as estimated from the vibration signal, is close to being proportional to bolt tension, except at very low tensions (Fig. 1(d)). To obtain an estimate of bolt tightness this way only requires a period of time of the order of a second where the user taps the bolt with a light hammer, which triggers measurement and data processing. However, experimental results revealed that this technique encounters two problems, for it to be presently useful in real applications: First the variability in results is too large, about twice that for a torque wrench. Figure 2(a) shows that the slope of the curves varies for separate experiments with similar increasing bolt tension, which suggests that the quantity ω/β is an unreliable feature for estimating bolt tension. A second fundamental problem is that the relative change in natural frequency is approximately proportional not only to bolt tension, but also to slenderness ratio. Thus, if only the natural frequency feature were to be used for estimating bolt tension, accuracy will drop off for the short and thick bolts that are often used in critical joints.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics, Karlsruhe Institute of Technology, Brüel and Kjær Sound and Vibration Measurement A/S
Contributors: Thomsen, J. J., Sah, S. M., Fidlin, A., Tcherniak, D.
Pages: 2
Publication date: 2017

Host publication information
Title of host publication: Proceedings of the 9th European Nonlinear Dynamics Conference
Publisher: CongressLine Ltd.
Editors: Stépán, G., Csernák, G.
ISBN (Electronic): 978-963-12-9168-1
Electronic versions: ConferencePresentation_2017_2.pdf

Wave propagation in axially moving periodic strings

The paper deals with analytically studying transverse waves propagation in an axially moving string with periodically modulated cross section. The structure effectively models various relevant technological systems, e.g. belts, thread lines, band saws, etc., and, in particular, roller chain drives for diesel engines by capturing both their spatial periodicity and axial motion. The Method of Varying Amplitudes is employed in the analysis. It is shown that the compound wave traveling in the axially moving periodic string comprises many components with different frequencies and wavenumbers. This is in contrast to non-moving periodic structures, for which all components of the corresponding compound wave feature the same frequency. Due to this “multi-frequency” character of the wave motion, the conventional notion of frequency band-gaps appears to be not applicable for the moving periodic strings. Thus, for such structures, by frequency band-gaps it is proposed to understand frequency ranges in which the primary component of the compound wave attenuates. Such frequency band-gaps can be present for a moving periodic string, but only if its axial velocity is lower than the transverse wave speed, and, the higher the axial velocity, the narrower the frequency band-gaps. The revealed effects could be of potential importance for applications, e.g. they indicate that due to spatial inhomogeneity, oscillations of axially moving periodic chains always involve a multitude of frequencies.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics, Russian Academy of Sciences
Contributors: Sorokin, V. S., Thomsen, J. J.
Pages: 133-144
Publication date: 2017
Peer-reviewed: Yes
Effects of quadratic and cubic nonlinearities on a perfectly tuned parametric amplifier

We consider the performance of a parametric amplifier with perfect tuning (two-to-one ratio between the parametric and direct excitation frequencies) and quadratic and cubic nonlinearities. A forced Duffing–Mathieu equation with appended quadratic nonlinearity is considered as the model system, and approximate analytical steady-state solutions and corresponding stabilities are obtained by the method of varying amplitudes. Some general effects of pure quadratic, and mixed quadratic and cubic nonlinearities on parametric amplification are shown. In particular, the effects of mixed quadratic and cubic nonlinearities may generate additional amplitude–frequency solutions. In this case an increased response and a more phase sensitive amplitude (phase between excitation frequencies) is obtained, as compared to the case with either pure quadratic or cubic nonlinearity. Furthermore, jumps and bi-stability in the amplitude–phase characteristics are predicted, supporting previously reported experimental observations.

Effects of weak nonlinearity on the dispersion relation and frequency band-gaps of a periodic Bernoulli–Euler beam

The paper deals with analytically predicting the effects of weak nonlinearity on the dispersion relation and frequency band-gaps of a periodic Bernoulli–Euler beam performing bending oscillations. Two cases are considered: (i) large transverse deflections, where nonlinear (true) curvature, nonlinear material and nonlinear inertia owing to longitudinal motions of the beam are taken into account, and (ii) midplane stretching nonlinearity. A novel approach is employed, the method of varying amplitudes. As a result, the isolated as well as combined effects of the considered sources of nonlinearities are
revealed. It is shown that nonlinear inertia has the most substantial impact on the dispersion relation of a nonuniform beam by removing all frequency band-gaps. Explanations of the revealed effects are suggested, and validated by experiments and numerical simulation.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Sorokin, V. S., Thomsen, J. J.
Number of pages: 22
Publication date: 2016
Peer-reviewed: Yes

Publication information
Journal: Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences
Volume: 472
Issue number: 2186
Article number: 20150751
ISSN (Print): 1364-5021
Ratings:
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 1.85 SJR 0.832 SNIP 1.237
Web of Science (2016): Impact factor 2.146
Web of Science (2016): Indexed yes
Original language: English
Keywords: Elastic wave propagation, Dispersion relation, Frequency band-gaps, Weak nonlinearity, Periodic Bernoulli–Euler beam, Method of varying amplitudes
Electronic versions:
PostPrint_2016_2.pdf
Effects_of_weak_nonlinearity_on_dispersion_relation_and_frequency_band_gaps_of_a_periodic_Bernoulli_Euler_beam.pdf
DOIs:
10.1098/rspa.2015.0751
URLs:
Source: FindIt
Source-ID: 2291923719
Research output: Contribution to journal › Journal article – Annual report year: 2016 › Research › peer-review

Kinematic and dynamic modeling and approximate analysis of a roller chain drive
A simple roller chain drive consisting of two sprockets connected by tight chain spans is investigated. First, a kinematic model is presented which include both spans and sprockets. An approach for calculating the chain wrapping length is presented, which also allows for the exact calculation of sprocket center positions for a given chain length. The kinematic analysis demonstrates that the total length of the chain wrapped around the sprockets generally varies during one tooth period. Analytical predictions for the wrapping length are compared to multibody simulation results and show very good agreement. It is thereby demonstrated that chain drives with tight chain spans must include compliant components to function. Second, a dynamic model is presented which includes the two spans and the driven sprocket. Assuming the presence of a stationary operating state, the presented dynamic model allows for analytical studies of the coupled motion of the chain spans and driven sprocket. Parametric excitation of the spans come from sprocket angular displacements, and the driven sprocket acts as a boundary which can be compliant in the axial direction. External transverse excitation of the spans comes from polygonal action, and is treated through kinematic forcing at the moving string boundaries. Perturbation analysis of the model is carried out using the method of multiple scales. Results show a multitude of internal and external resonance conditions, and some examples are presented of both decoupled and coupled motion. Together, the kinematic and dynamic model are aimed toward providing a framework for conducting and understanding both numerical, and experimental investigations of roller chain drive dynamics.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Fuglede, N., Thomsen, J. J.
Pages: 447-470
Publication date: 2016
Peer-reviewed: Yes

Publication information
Journal: Journal of Sound and Vibration
Kinematics of roller chain drives - Exact and approximate analysis

An exact and approximate kinematic analysis of a roller chain drive modeled as a four-bar mechanism is presented. The span connects the sprockets such that they rotate in the same direction, and the sprocket size, number of teeth, and shaft center distance can be arbitrary. The driven sprocket angular position, velocity and acceleration, as well as span length, are calculated and their (discontinuous) variation with driver angular position and main design parameters is illustrated. Kinematic predictions for the chain span motion are compared to results of multibody simulation, and there is seen to be very good agreement. All together this gives new insights into the characteristics of chain drive kinematics and the influence of main design parameters.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Fuglede, N., Thomsen, J. J.
Pages: 17-32
Publication date: 2016
Peer-reviewed: Yes

Publication information
Journal: Mechanism and Machine Theory
Volume: 100
ISSN (Print): 0094-114X
Ratings:
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 3.06 SJR 1.136 SNIP 2.47
Web of Science (2016): Impact factor 2.577
Web of Science (2016): Indexed yes
Original language: English
Keywords: Chain drives, Four-bar mechanism, Kinematics, Multibody simulation, Roller chain
Electronic versions:
POSTPRINT_MECHMT_D_14_00558_Manuscript_revised.pdf. Embargo ended: 13/02/2018
DOIs:
10.1016/j.mechmachtheory.2016.01.009
Source: FindIt
Source-ID: 2292312916
Research output: Contribution to journal › Journal article – Annual report year: 2016 › Research › peer-review

Scanning laser Doppler vibrometry

With a Scanning Laser Doppler Vibrometer (SLDV) a vibrating surface is automatically scanned over predefined grid points, and data processed for displaying vibration properties like mode shapes, natural frequencies, damping ratios, and operational deflection shapes. Our SLDV – a PSV-500H from Polytec Inc. – was acquired and put to operation in October 2014, paid by a sub-donation of DKK 1.5 mill. of the total VILLUM CASMaT grant. Opening possibilities of measuring complicated vibration shapes of almost any object – contactless, mostly automatically, and with only a single transducer – this costly equipment had been top priority on our wish list for many years.
Effects of weak nonlinearity on dispersion relations and frequency band-gaps of periodic structures

The analysis of the behaviour of linear periodic structures can be traced back over 300 years, to Sir Isaac Newton, and still attracts much attention. An essential feature of periodic structures is the presence of frequency band-gaps, i.e. frequency ranges in which waves cannot propagate. Determination of band-gaps and the corresponding attenuation levels is an important practical problem. Most existing analytical methods in the field are based on Floquet theory; e.g. this holds for the classical Hill’s method of infinite determinants, and the method of space-harmonics. However, application of these for nonlinear problems is impossible or cumbersome, since Floquet theory is applicable for linear systems only. Thus the nonlinear effects for periodic structures are not yet fully uncovered, while at the same time applications may demand effects of nonlinearity on structural response to be accounted for. The present work deals with analytically predicting dynamic responses for nonlinear continuous elastic periodic structures. Specifically, the effects of weak nonlinearity on the dispersion relation and frequency band-gaps of a periodic Bernoulli-Euler beam performing bending oscillations are analyzed. Modulation of the beam structural properties is not required to be small or piecewise constant. Various sources of nonlinearity are analyzed, namely, nonlinear (true) curvature, nonlinear inertia due to longitudinal motions of the beam, nonlinear material, and also nonlinearity associated with mid-plane stretching. A novel approach, the Method of Varying Amplitudes, is employed. This implies representing a solution in the form of a harmonic series with varying amplitudes; however, in contrast to averaging methods, the amplitudes are not required to vary slowly in space. As a result, a shift of band-gaps to a higher (or lower) frequency range is revealed, while the width of the band-gaps appears relatively insensitive to (weak) nonlinearity. The results are validated by numerical simulation, and explanations of the effects are suggested.

Eigenfrequencies and eigenmodes of a beam with periodically continuously varying spatial properties

A beam with periodically continuously varying spatial properties is analyzed. This structure is a generic model for various systems widely used in industry, e.g. risers, rotor blades, and similar. The aim is to reveal effects of periodic spatial modulation both on the beam eigenfrequencies and eigenmodes. Special attention is given to “mid-frequency” eigenmodes having period of the same order as the period of modulation, which cannot be captured by the conventional analytical methods. In particular, the paper addresses prediction of bandgaps and their influence on the distribution of eigenfrequencies. For analyzing the problem considered, the method of varying amplitudes is employed. A connection of this method with the classical Hill’s infinite determinant method and the method of space-harmonics is noted. A dispersion relation of the considered non-uniform periodic structure is obtained, and values of the modulation amplitudes at which
frequency bandgaps arise are determined. It is shown that eigenfrequencies of the beam can lie within the bandgaps, and that such eigenfrequencies can be considerably affected by modulation. It is revealed that there is an abrupt shift in the effect of modulation on eigenfrequencies, and that modulations of the beam mass per unit length and of the beam stiffness affect them oppositely. It is shown that eigenmodes having a period close to the period of modulation comprise a long-wave component; this illustrates the capacity of non-uniform structures to sustain long-wave oscillations on comparatively high frequencies.

Experimental bifurcation analysis—Continuation for noise-contaminated zero problems
Noise contaminated zero problems involve functions that cannot be evaluated directly, but only indirectly via observations. In addition, such observations are affected by a non-deterministic observation error (noise). We investigate the application of numerical bifurcation analysis for studying the solution set of such noise contaminated zero problems, which is highly relevant in the context of equation-free analysis (coarse grained analysis) and bifurcation analysis in experiments, and develop specialized algorithms to address challenges that arise due to the presence of noise. As a working example, we demonstrate and test our algorithms on a mechanical nonlinear oscillator experiment using control based continuation, which we used as a main application and test case for development of the Coco compatible Matlab toolbox Continex that implements our algorithms.
Frequency detuning effects for parametrically and directly excited elastic structures

This study investigates the frequency detuning effects of parametric and direct excitation for near-resonant nonlinear structural vibrations. Specifically, the detuning effects of a two-to-one frequency ratio between the parametric and direct excitation, and of a drift in natural frequency, are studied. These effects are investigated theoretically using a Duffing-Mathieu equation as the model system, and experimentally using a cantilever beam as the model object. The approximate analytical responses are derived using the method of varying amplitudes, and compared with results of direct numerical integration and experiments showing good agreement. For frequency detuned superthreshold parametric excitation some of the theoretical frequency-amplitude solution branches appear to merge. For some ranges of parametric excitation frequency a drop in experimental steady-state vibration amplitude was found, indicating performance degradation whereas for other frequency ranges, frequency detuning may yield an increased steady-state vibration amplitude. This makes frequency detuning a feature which can purposefully be avoided or utilized, dependent on the application.

The method of varying amplitudes for solving (non)linear problems involving strong parametric excitation

Parametrically excited systems appear in many fields of science and technology, intrinsically or imposed purposefully; e.g. spatially periodic structures represent an important class of such systems [4]. When the parametric excitation can be considered weak, classical asymptotic methods like the method of averaging [2] or multiple scales [6] can be applied. However, with many practically important applications this simplification is inadequate, e.g. with spatially periodic structures it restricts the possibility to affect their effective dynamic properties by a structural parameter modulation of considerable magnitude. Approximate methods based on Floquet theory [4] for analyzing problems involving parametric excitation, e.g. the classical Hill’s method of infinite determinants [3,4], can be employed also in cases of strong excitation; however, with Floquet theory being applicable only for linear systems, this is impossible or rather cumbersome for combined parametric and direct excitation, or with nonlinearity.
Vibration suppression for strings with distributed loading using spatial cross-section modulation

A problem of vibration suppression in any preassigned region of a bounded structure subjected to action of an external time-periodic load which is distributed over its domain is considered. A passive control is applied, in which continuous spatially periodic modulations of structural parameters are used as a means for vibration suppression. As an example, stationary vibrations of a string under action of a distributed time-periodic load are studied. This system in a simplified form models such processes as interaction between membranes and colloids, oscillations of transmission lines under action of rain and wind, and dynamics of suspension bridges and stay cables. Suppression of vibration in predefined regions of the string is performed by continuous spatial modulation of its cross-section.

For analyzing the problem considered a novel approach named the method of varying amplitudes is employed. This approach is applicable for solving differential equations without a small parameter, and may be considered as a natural continuation of the classical methods of harmonic balance and averaging. As a result, optimal parameters for the string cross-sectional area modulation are determined for the cases of harmonically, uniformly and arbitrarily distributed load, which allows for completely suppressing or considerably reducing vibration in the prescribed part of the string (compared to the case without modulation).

Weakly nonlinear dispersion and stop-band effects for periodic structures

Continua and structures composed of periodically repeated elements (cells) are used in many fields of science and technology. Examples of continua are composite materials, consisting of alternating volumes of substances with different properties, mechanical filters and wave guides. Examples of engineering periodic structures include some building frames, bridge trusses, cranes, railway tracks, and compound pipes. Thus dynamic analysis of spatially periodic structures is relevant for many applications, and attracts much attention. An essential feature of periodic structures is the presence of frequency band-gaps, i.e. frequency ranges in which elastic waves cannot propagate. Most existing analytical methods in the field are based on Floquet theory [1]; e.g. this holds for the classical Hill’s method of infinite determinants [1,2], and themethod of space-harmonics [3]. However, application of these methods for studying nonlinear problems is impossible or cumbersome, since Floquet theory is applicable only for linear systems. Thus the nonlinear effects for periodic structures are not yet fully uncovered, while at the same time applications may demand effects of nonlinearity on structural response to be accounted for. The paper deals with analytically predicting dynamic response for nonlinear elastic structures with a continuous periodic variation in structural properties. Specifically, for a Bernoulli-Euler beam with a spatially continuous modulation of structural properties in the axial direction, not necessarily small, we consider the effects of weak nonlinearity on the dispersion relation and frequency band-gaps. A novel approach, the Method of Varying Amplitudes [4], is employed. This approach is inspired by the method of direct separation of motions [5], and may be considered a natural
continuation of the classical methods of harmonic balance [2] and averaging [6]. It implies representing a solution in the form of a harmonic series with varying amplitudes, but, in contrast to averaging methods, the amplitudes are not required to vary slowly. The approach is strongly related also to Hill's method of infinite determinants [1,2], and to the method of space-harmonics [3]. As a result, a shift of band-gaps to a higher frequency range is revealed, while the width of the band-gaps appears relatively insensitive to (weak) nonlinearity. The results are validated by numerical simulation, and explanations of the effects suggested. The work is carried out with financial support from the Danish Council for Independent Research and COFUND: DFF – 1337-00026

**General information**
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Sorokin, V., Thomsen, J. J.
Number of pages: 1
Publication date: 2015
Peer-reviewed: Yes
Event: Abstract from 5th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, The Island of Crete, Greece.
Electronic versions:
JITp_81_SorokinVS_Thomsen_NonlinDispersion_StopbandEffectsForPeriodicStructs_COMPDYN2015_Crete_.pdf
Source: PublicationPreSubmission
Source-ID: 110670660
Research output: Contribution to conference › Conference abstract for conference – Annual report year: 2015 › Research › peer-review

**Bifurcation analysis of a smoothed model of a forced impacting beam and comparison with an experiment**
A piecewise-linear model with a single degree of freedom is derived from first principles for a driven vertical cantilever beam with a localized mass and symmetric stops. The aim is to show that this model constitutes a considerable step toward developing a vibro-impact model that is able to make qualitative and quantitative predictions of the observed dynamics. The resulting piecewise-linear dynamical system is smoothed by a switching function (nonlinear homotopy). For the chosen smoothing function, it is shown that the smoothing can induce bifurcations in certain parameter regimes. These induced bifurcations disappear when the transition of the switching is sufficiently and increasingly localized as the impact becomes harder. The bifurcation structure of the impact oscillator response is investigated via the one- and two-parameter continuation of periodic orbits in the driving frequency and/or forcing amplitude. The results are in good agreement with experimental measurements.

**General information**
Publication status: Published
Organisations: Department of Applied Mathematics and Computer Science, Mathematics, Department of Mechanical Engineering, Solid Mechanics, Dynamical Systems, University of Auckland
Contributors: Elmegård, M., Krauskopf, B., Osinga, H., Starke, J., Thomsen, J. J.
Pages: 951–966
Publication date: 2014
Peer-reviewed: Yes

**Publication information**
Journal: Nonlinear Dynamics
Volume: 77
ISSN (Print): 0924-090X
Ratings:
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 3.07 SJR 1.329 SNIP 1.733
Web of Science (2014): Impact factor 2.849
Web of Science (2014): Indexed yes
Original language: English
Keywords: Vibro-impacting beam, Piecewise-linear, Piecewise-smooth, Smoothing, Cantilever beam, Single-degree-of-freedom model
DOI:
10.1007/s11071-014-1353-x
Source: PublicationPreSubmission
Source-ID: 98935097
Research output: Contribution to journal › Journal article – Annual report year: 2014 › Research › peer-review
CONTINEX: A Toolbox for Continuation in Experiments

CONTINEX is a MATLAB toolbox for bifurcation analysis based on the development platform COCO (computational continuation core). CONTINEX is specifically designed for coupling to experimental test specimen via DSPACE, but provides also interfaces to SIMULINK-, ODE-, and so-called equation-free models. The current version of the interface for experimental set-ups implements an algorithm for tuning control parameters, a robust noise-tolerant covering algorithm, and functions for monitoring (in)stability. In this talk we will report on experiments with an impact oscillator with magnetic actuators and algorithmic challenges we were facing during toolbox development.

General information
Publication status: Published
Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, Department of Mechanical Engineering, Solid Mechanics
Contributors: Schilder, F., Bureau, E., Santos, I., Thomsen, J. J., Starke, J.
Number of pages: 2
Publication date: 2014

Experimental bifurcation analysis of an impact oscillator – Determining stability

We propose and investigate three different methods for assessing stability of dynamical equilibrium states during experimental bifurcation analysis, using a control-based continuation method. The idea is to modify or turn off the control at an equilibrium state and study the resulting behavior. As a proof of concept the three methods are successfully implemented and tested for a harmonically forced impact oscillator with a hardening spring nonlinearity, and controlled by electromagnetic actuators. We show that under certain conditions it is possible to quantify the instability in terms of finite-time Lyapunov exponents. As a special case we study an isolated branch in the bifurcation diagram brought into existence by a 1:3 subharmonic resonance. On this isola it is only possible to determine stability using one of the three methods, which is due to the fact that only this method guarantees that the equilibrium state can be restored after measuring stability.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Department of Applied Mathematics and Computer Science, Dynamical Systems, Mathematics, Solid Mechanics
Contributors: Bureau, E., Schilder, F., Elmegård, M., Santos, I., Thomsen, J. J., Starke, J.
Pages: 5464–5474
Publication date: 2014
Peer-reviewed: Yes

Publication information
Journal: Journal of Sound and Vibration
Volume: 333
Issue number: 21
ISSN (Print): 0022-460X
Ratings:
BFI (2014): BFI-level 2
Scopus rating (2014): CiteScore 2.54 SJR 1.52 SNIP 2.27
Web of Science (2014): Impact factor 1.813
Web of Science (2014): Indexed yes
Original language: English
DOI:
10.1016/j.jsv.2014.05.032
Source: PublicationPreSubmission
Source-ID: 98935117
Research output: Contribution to journal › Journal article – Annual report year: 2014 › Research › peer-review
Experiments in nonlinear dynamics using control-based continuation: Tracking stable and unstable response curves

We show how to implement control-based continuation in a nonlinear experiment using existing and freely available software. We demonstrate that it is possible to track the complete frequency response, including the unstable branches, for a harmonically forced impact oscillator.

General information
Publication status: Published
Organisations: Department of Applied Mathematics and Computer Science, Dynamical Systems, Department of Mechanical Engineering, Solid Mechanics
Contributors: Bureau, E., Schilder, F., Santos, I., Thomsen, J. J., Starke, J.
Number of pages: 2
Publication date: 2014

Host publication information
Title of host publication: Proceedings of the 8th European Nonlinear Dynamics Conference (ENOC 2014)
Publisher: Technische Universität Wien

Jumps and bi-stability in the phase-gain characteristics of a nonlinear parametric amplifier

This work experimentally investigates the impact of nonlinearity on macromechanical parametric amplification. For a strong cubic stiffness nonlinearity we observe jumps in gain (ratio of steady-state vibration amplitude of the externally and parametrically excited system, to vibration amplitude of the externally excited only system) as function of the phase between the external and parametric excitation. These jumps occur at different phase values dependent on up- and downsweeps. Furthermore, an increasing asymmetric phase-gain relationship was observed for strong nonlinearity.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics, Eindhoven University of Technology
Contributors: Neumeyer, S., van de Looij, R., Thomsen, J. J.
Number of pages: 2
Publication date: 2014

Host publication information
Title of host publication: ENOC 2014 - Proceedings of 8th European Nonlinear Dynamics Conference
Publisher: Vienna University of Technology

Experimental bifurcation analysis of an impact oscillator - Tuning a non-invasive control scheme

We investigate a non-invasive, locally stabilizing control scheme necessary for an experimental bifurcation analysis. Our test-rig comprises a harmonically forced impact oscillator with hardening spring nonlinearity controlled by electromagnetic actuators, and serves as a prototype for electromagnetic bearings and other machinery with build-in actuators. We propose a sequence of experiments that allows one to choose optimal control-gains, filter parameters and settings for a continuation method without a priori study of a model. Depending on the algorithm for estimating the Jacobian required by Newton's method we find two almost disjoint sets of suitable control parameters. Control-based continuation succeeds reliably in producing the full bifurcation diagram including both stable and unstable equilibrium states for an appropriately tuned controller.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics, Eindhoven University of Technology
Contributors: Bureau, E., Schilder, F., Santos, I., Thomsen, J. J., Starke, J.
Pages: 5883–5897
Publication date: 2013
Peer-reviewed: Yes
Macromechanical parametric amplification

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Neumeyer, S., Thomsen, J. J.
Number of pages: 1
Publication date: 2013
Peer-reviewed: No
Event: Poster session presented at DCAMM 14th Internal Symposium, Nyborg, Denmark.
Electronic versions:
Poster14thDCAMM_Neumeyer2013_v5.pdf
Source: dtu
Source-ID: u::7875

Macromechanical parametric amplification with a base-excited doubly clamped beam

Parametric amplification is realized by adding parametric excitation to externally driven near-resonant oscillations. The effect of specific cubic nonlinearities on the parametrically amplified steady-state vibrations and gain is investigated theoretically. Here, gain is defined as the ratio of steady-state vibration amplitude of the directly and parametrically excited system, to vibration amplitude of the directly excited only system. The nonlinear effect of midplane stretching is compared to the effects of nonlinear inertia and curvature. An approximate analytical expression for the vibration amplitude is derived. For a given small level of transverse displacement for both the cantilever and doubly clamped beam, the effect of midplane stretching is dominant compared to those caused by nonlinear inertia and curvature. It was found that the beam slenderness ratio can be used as an effective design parameter for parametric amplifiers.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Neumeyer, S., Thomsen, J. J.
Number of pages: 8
Publication date: 2013

Host publication information
Title of host publication: 11th International Conference on Vibration Problems
Editor: Dimitrovova, Z.
Keywords: Parametric amplification, Nonlinear oscillations, Nonlinear Effects, Gain, Doubly Clamped Beam
Electronic versions:
MACROMECHANICAL_PARAMETRIC_AMPLIFICATION.pdf
Source: dtu
Source-ID: u::7876

Roller chain drive vibration analysis based on a string model with boundaries moving non-smoothly

General information
Experimental Bifurcation Analysis By Control-based Continuation - Determining Stability

The newly developed control-based continuation technique has made it possible to perform experimental bifurcation analysis, e.g. to track stable as well as unstable branches of frequency responses directly in experiments. The method bypasses mathematical models, and systematically explores how vibration characteristics of dynamical systems change under variation of parameters. The method employs a control scheme to modify the response stability. While this facilitates exploration of the unstable branches of a bifurcation diagram, it unfortunately makes it impossible to distinguish previously stable and unstable equilibrium states. We present the ongoing work of developing and applying the control-based continuation method to an experimental mechanical test-rig, consisting of a harmonically forced nonlinear impact oscillator controlled by electromagnetic actuators. Furthermore we propose and test ideas on how to determine the stability of equilibria states during continuation.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics, Department of Mathematics, Dynamical systems
Contributors: Bureau, E., Santos, I., Thomsen, J. J., Schilder, F., Starke, J.
Number of pages: 8
Pages: DETC2012-70616
Publication date: 2012

Host publication information
Title of host publication: Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
Publisher: American Society of Mechanical Engineers
Source: dtu
Source-ID: u::4360
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2012 › Research › peer-review

Macroscale mechanical domain parametric amplification: superthreshold pumping and optimal excitation parameters

This work investigates theoretically and experimentally the phenomenon of parametric amplification in a macroscale mechanical context, using a base-excited tilted cantilever beam as the model object. It demonstrates that an optimum mix between selected excitation parameters exists, that parametric amplification is possible for the second vibration mode, that the detuned case is phase lag insensitive, and that superthreshold pumping changes the gain/phase lag relationship, the phase lag range for which amplification and attenuation is realized, the optimum phase lag, and the attainable gain.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Neumeyer, S., Thomsen, J. J.
Number of pages: 4
Publication date: 2012

Host publication information
Title of host publication: EUROMECH Colloquium 532 : 1st International Colloquium on Time periodic systems (TPS). Current trends in theory and application
Publisher: Technische Universität Darmstadt
Electronic versions:
JJTp-64_EUROMECH-532-ExtAbstract–Neumeyer&Thomsen.pdf
Vibrations of axially moving strings with in-plane oscillating supports
For a traveling string moving in the plane we analyze analytically the transverse vibrations arising from oscillation of the string supports. Of special interest is the excitation typical of roller chain drives, where meshing between chain and sprockets cause both noise and vibration. Considering a uniform, heavy string moving at subcritical speed with prescribed endpoint motion, and ignoring longitudinal inertia, one obtains a continuous, nonlinear, gyroscopic, parametrically and externally excited system. By employing a single-mode approximation, using velocity dependent mode shapes, the system response is approximated using the method of multiple scales. Vibrations from support oscillations characteristic of roller chain drives are investigated. Conclusions about critical values for chain drive parameters such as pretension and meshing frequency are sought and identified.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Fuglede, N., Thomsen, J. J.
Number of pages: 4
Publication date: 2012
Peer-reviewed: No
Event: Abstract from EUROMECH Colloquium 532, Darmstadt, Germany.
Electronic versions:
Fuglede-Thomsen_EuroMech532_revised.pdf

Bibliographical note
1st International Colloquium on Time-periodic Systems
Source: dtu
Source-ID: u::4051
Research output: Contribution to conference › Conference abstract for conference – Annual report year: 2012 › Research

Experimental bifurcation analysis for a driven nonlinear flexible pendulum using control-based continuation
We present a software toolbox that allows to apply continuation methods directly to a controlled lab experiment. This toolbox enables us to systematically explore how stable and unstable steady state periodic vibrations depend on parameters. The toolbox is implemented partly in MATLAB and partly on a dSPACE realtime controller board. Its functionality is tested on a driven mechanical oscillator with a strong impact nonlinearity, controlled with electromagnetic actuators. We show how to tune a controller so that the steady state dynamics of the controlled experiment matches that of the corresponding un-controlled experiment.

General information
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering, Dynamical systems, Department of Mathematics
Contributors: Bureau, E., Schilder, F., Santos, I., Thomsen, J. J., Starke, J.
Publication date: 2011

Host publication information
Title of host publication: 7th European Nonlinear Dynamics Conference
Electronic versions:
ENOC2011_ExtendedPaper.pdf
Source: orbit
Source-ID: 278450
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2011 › Research › peer-review

Experimental bifurcation by using control-based continuation
General information
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering, Dynamical systems, Department of Mathematics
Contributors: Bureau, E., Santos, I., Thomsen, J. J., Starke, J., Schilder, F., Elmegård, M.
Publication date: 2011
Experimental investigation of zero phase shift effects for Coriolis flowmeters due to pipe imperfections

Theoretical investigations of a single, straight, vibrating, fluid-conveying pipe have resulted in simple analytical expressions for the approximate prediction of the spatial shift in vibration phase. The expressions have lead to hypotheses for real Coriolis flowmeters (CFMs). To test these, the flexural vibrations of two bent, parallel, non-fluid-conveying pipes are studied experimentally, employing an industrial CFM. Special attention has been paid on the phase shift in the case of zero mass flow, i.e. the zero shift, caused by various imperfections to the "perfect" CFM, i.e. non-uniform pipe damping and mass, and on ambient temperature changes. Experimental observations confirm the hypothesis that asymmetry in the axial distribution of damping will induce zero shifts similar to the phase shifts due to fluid flow. Axially symmetrically distributed damping was observed to influence phase shift at an order of magnitude smaller than the primary effect of mass flow, while small added mass and ambient temperature changes induced zero shifts two orders of magnitude smaller than the phase shifts due to mass flow. The order of magnitude of the induced zero shifts indicates that non-uniform damping, added mass as well as temperature changes could be causes contributing to a time-varying measured zero shift, as observed with some commercial CFMs. The conducted experimental tests of the theoretically based hypotheses have shown that simple mathematical models and approximate analysis allow general conclusions, that may provide a direct insight, and help increasing the benefit of time consuming numerical simulations and laboratory experiments.

Guiding Simulations and Experiments using Continuation

When applying continuation of periodic solutions to high-dimensional finite element models one might face a dilemma. The mesh resolution and thus the dimension N of the model are typically chosen such that a given computer system can store the information necessary to perform one integration step for dimension N, but not for larger dimensions. In other words, a model is usually implemented as a carefully derived implicit integration scheme tailored for numerically stable simulations with the highest spacial resolution admitted by the computational power available. On the other hand, stable numerical methods for periodic solutions, for example, multiple shooting or collocation, typically require the simultaneous storage and manipulation of information for K>1 states, which would imply that periodic solutions cannot be computed without a significant reduction of the model's resolution. The recently developed method of control based continuation allows the continuation of periodic solutions without a reduction of the model resolution, and even directly in physical experiments. Moreover, both a simulation as well as an experiment can run asynchronously from the actual continuation method, which
communicates with the simulation or experiment by setting a control target and by taking measurements. The key ideas of this approach are (1) to introduce a control scheme that locally stabilizes periodic solutions without perturbing them, and (2) to use continuation to guide the simulation or experiment around folds and through bifurcation points. In this talk we will present a Matlab toolbox for control based continuation and illustrate its application with a lab experiment of an impact oscillator that exhibits a large hysteresis loop. We will indicate current challenges with this method and how we intend to tackle them.

**General information**
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering, Dynamical systems, Department of Mathematics, IPVS Stuttgart
Contributors: Bureau, E., Schilder, F., Avrutin, V., Starke, J., Santos, I., Thomsen, J. J.
Publication date: 2011

**Event information**
Event: School and Conference on Computational Methods in Dynamics
Location: Trieste, Italy
Electronic versions:
prod11324491346398.talk[1].pdf
Source: orbit
Source-ID: 316744
Research output: Non-textual form › Sound/Visual production (digital) – Annual report year: 2011 › Research

**Low-dimensional approximations for Finite Element Models of mechanical systems**
The present study is dedicated to the dimension reduction of high-dimensional FE models of mechanical systems in which low-dimensional behaviour is observable. A low-dimensional model of the such a FE model is constructed and the bifurcation diagram of the low-dimensional system is compared with that of the FE model in order to investigate the range of validity of the low-dimensional model.

**General information**
Publication status: Published
Organisations: Dynamical systems, Department of Mathematics, Solid Mechanics, Department of Mechanical Engineering, Technical University of Denmark
Contributors: Elmegaard, M., Starke, J., Schilder, F., Thomsen, J. J.
Publication date: 2011

**Host publication information**
Title of host publication: 7th European Nonlinear Dynamics Conference
Electronic versions:
Source: orbit
Source-ID: 314408
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2011 › Research › peer-review

**Predicting phase shift effects for vibrating fluid-conveying pipes due to Coriolis forces and fluid pulsation**
Knowing the influence of fluid flow perturbations on the dynamic behavior of fluid-conveying pipes is of relevance, e.g., when exploiting flow-induced oscillations of pipes to determine the fluids mass flow or density, as done with Coriolis flow meters (CFM). This could be used in the attempts to improve accuracy, precision, and robustness of CFMs. A simple mathematical model of a fluid-conveying pipe is formulated and the effect of pulsating fluid flow is analyzed using a multiple time scaling perturbation analysis. The results are simple analytical predictions for the transverse pipe displacement and approximate axial shift in vibration phase. The analytical predictions are tested against pure numerical solution using representative examples, showing good agreement. Fluid pulsations are predicted not to influence CFM accuracy, since proper signal filtering is seen to allow the determination of the correct mean phase shift. Large amplitude motions, which could influence CFM robustness, do not appear to be induced by the investigated fluid pulsation. Pulsating fluid of the combination resonance type could, however, influence CFMs robustness, if induced pipe motions go unnoticed and uncontrolled during CFM operation by feedback control. The analytical predictions offer an immediate insight into how fluid pulsation affects phase shift, which is a quantity measured by CFMs to estimate the mass flow, and lead to hypotheses for more complex geometries, i.e. industrial CFMs. The validity of these hypotheses is suggested to be tested using laboratory experiments, or detailed computational models taking fluid–structure interaction into account.

**General information**
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Enz, S., Thomsen, J. J.
Roller chain drive analysis: simplified modeling and analysis of the dynamic effects of meshing

Transverse vibration of a roller chain and the effects of the interaction with sprockets is examined analytically. Modeling the chain as a uniform string, we consider the meshing process either as a moving boundary, or as boundary impacts and apply perturbation methods to predict dynamical responses.

Analytical predictions for vibration phase shifts along fluid-conveying pipes due to Coriolis forces and imperfections

Resonant vibrations of a fluid-conveying pipe are investigated, with special consideration to axial shifts in vibration phase accompanying fluid flow and various imperfections. This is relevant for understanding elastic wave propagation in general, and for the design and trouble-shooting of phase-shift measuring devices such as Coriolis mass flowmeters in particular. Small imperfections related to elastic and dissipative support conditions are specifically addressed, but the suggested approach is readily applicable to other kinds of imperfection, e.g. non-uniform stiffness or mass, non-proportional damping, weak nonlinearity, and flow pulsation. A multiple time scaling perturbation analysis is employed for a simple model of an imperfect fluid-conveying pipe. This leads to simple analytical expressions for the approximate prediction of phase shift, providing direct insight into which imperfections affect phase shift, and in which manner. The analytical predictions are tested against results obtained by pure numerical analysis using a Galerkin expansion, showing very good agreement. For small imperfections the analytical predictions are thus comparable in accuracy to numerical simulation, but provide much more insight. This may aid in creating practically useful hypotheses that hold more generally for real systems of complex geometry, e.g. that asymmetry or non-proportionality in axial distribution of damping will induce phase shifts in a manner similar to that of fluid flow, while the symmetric part of damping as well as non-uniformity in mass or stiffness do not affect phase shift. The validity of such hypotheses can be tested using detailed fluid-structure interaction computer models or laboratory experiments.
Experimental Detection and Quantification of Structural Nonlinearity Using Homogeneity and Hilbert Transform Methods

All real structures are inherently nonlinear. Whether a structure exhibits linear or nonlinear behavior, depends mainly on the excitation level. So far no unequivocal framework for experimental detection, localization, and characterization of structural nonlinearities from dynamic measurements exists. The present study suggests a framework for the detection of structural nonlinearities. Two methods for detection are compared, the homogeneity method and a Hilbert transform based method. Based on these two methods, a nonlinearity index is suggested. Through simulations and laboratory experiments it is demonstrated, for a simple but representative nonlinear structure, that both detection methods are able to detect even weak nonlinearities, and that the nonlinearity index provides a sensitive and robust measure of nonlinearity. For a range of input force amplitudes, it is shown that it is possible to estimate a systems linear and nonlinear regimes in terms of input amplitude, and asses the strength of the nonlinearity.
High-frequency effects in 1D spring-mass systems with strongly non-linear inclusions
This work generalises the possibilities to change the effective material or structural properties for low frequency (LF) wave propagation, by using high-frequency (HF) external excitation combined with strong non-linear and non-local material behaviour. The effects are demonstrated on 1D chain-like systems with embedded non-linear parts, where the masses interact with a limited set of neighbour masses. The presented analytical and numerical results show that the effective properties for LF wave propagation can be altered by establishing HF standing waves in the non-linear regions of the chain. The changes affect the effective stiffness and damping of the system.

Motions of elastic solids in fluids under vibration
Motion of a rigid or deformable solid in a viscous incompressible fluid and corresponding fluid–solid interactions are considered. Different cases of applying high frequency vibrations to the solid or to the surrounding fluid are treated. Simple formulas for the mean velocity of the solid are derived, under the assumption that the regime of the fluid flow induced by its motion is turbulent and the fluid resistance force is nonlinearly dependent on its velocity. It is shown that vibrations of a fluid’s volume slow down the motion of a submerged solid. This effect is much pronounced in the case of a deformable solid (i.e., gas bubble) exposed to near-resonant excitation. The results are relevant to the theory of gravitational enrichment of raw materials, and also contribute to the theory of controlled locomotion of a body with an internal oscillator in continuous deformable (solid or fluid) media.
Phase shift effects for vibrating pipes conveying pulsating fluid

Predicting phase shift of elastic waves in pipes due to fluid flow and imperfections

Using high-frequency vibrations and non-linear inclusions to create metamaterials with adjustable effective properties
force characteristics.

**General information**
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Lazarov, B. S., Thomsen, J. J.
Pages: 90-97
Publication date: 2009
Peer-reviewed: Yes

**Publication information**
Journal: International Journal of Non-Linear Mechanics
Volume: 44
Issue number: 1
ISSN (Print): 0020-7462
Ratings:
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 1.124 SNIP 1.505
Web of Science (2009): Indexed yes
Original language: English
Keywords: Non-linearity, Stiffening, Metamaterials, High-frequency excitation, Wave propagation
DOIs: 10.1016/j.ijnonlinmec.2008.09.001
Source: orbit
Source-ID: 233021
Research output: Contribution to journal › Journal article – Annual report year: 2009 › Research › peer-review

**Dynamics of fluid-conveying pipes: effects of velocity profiles**
Varying velocity profiles and internal fluid loads on fluid-conveying pipes are investigated. Different geometric layouts of the fluid domain and inflow velocity profiles are considered. It is found that the variation of the velocity profiles along the bended pipe is considerable. A determination of the resulting fluid loads on the pipe walls is of interest e.g. for evaluating the dynamical behaviour of lightly damped structures like Coriolis flow meters.

**General information**
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering
Contributors: Enz, S., Thomsen, J. J.
Publication date: 2008
Peer-reviewed: Yes
Event: Poster session presented at 22nd International Congress of Theoretical and Applied Mechanics, Adelaide, Australia.
Keywords: fluid-conveying pipes, velocity profile, Coriolis flowmeters
URLs:
Source: orbit
Source-ID: 233347
Research output: Contribution to conference › Poster – Annual report year: 2008 › Research › peer-review

**Effective properties of mechanical systems under high-frequency excitation at multiple frequencies**
Effects of strong high-frequency excitation at multiple frequencies (multi-HFE) are analyzed for a class of generally nonlinear systems. The effects are illustrated for a simple pendulum system with a vibrating support, and for a parametrically excited flexible beam. For the latter, theoretical predictions are supported by experimental observations, providing good agreement for a wide range of excitation conditions. The main effect of strong multi-HFE is to change the effective or apparent stiffness in a manner similar to that of mono-HFE, provided the HFE frequencies are well separated and non-resonant. Then the change in effective stiffness is proportional to the sum of squared excitation velocities, and the corresponding changes in equilibria, equilibrium stability, and natural frequencies can be computed as for the mono-HFE case. When there are two or more close-excitation frequencies, an additional contribution of slowly oscillating stiffness appears. This may cause strong parametric resonance at conditions that might not appear obvious, i.e. when the difference in two HFE frequencies is near twice an effective system natural frequency, which due to the HFE itself is shifted away from the natural frequency without HFE. Also, it is shown that strong multi-HFE can stabilize otherwise unstable equilibria, but generally this requires the frequencies to be well separated; thus, continuous broadband and random HFE does not have a uniquely stabilizing effect paralleling that of mono-HFE, or multi-HFE with non-close frequencies. The general results may be used to investigate or utilize general effects, or as a shortcut to calculate effective properties for specific systems, or to calculate averaged equations of motion that may be much faster to simulate numerically.
Near-elastic vibro-impact analysis by discontinuous transformations and averaging
We show how near-elastic vibro-impact problems, linear or nonlinear in-between impacts, can be conveniently analyzed by a discontinuity-reducing transformation of variables combined with an extended averaging procedure. A general technique for this is presented, and illustrated by calculating transient or stationary motions for different harmonic oscillators with stops or clearances, and self-excited friction oscillators with stops or clearances. First- and second-order analytical predictions are derived, and shown to agree to estimated accuracy with results of numerical simulation.

General information
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering
Contributors: Thomsen, J. J., Fidlin, A.
Pages: 386-407
Publication date: 2008
Peer-reviewed: Yes
Nontrivial effects of high-frequency excitation for strongly damped mechanical systems

Some non-trivial effects are investigated, which can occur if strongly damped mechanical systems are subjected to strong high-frequency (HF) excitation. The main result is a theoretical prediction, supported by numerical simulation, that for such systems the (quasi-)equilibrium states can change substantially with the level of damping. For example, a strongly damped pendulum, with a hinge vibrated at high frequency along an elliptical path with horizontal or vertical axis, will line up along a line offset from the vertical; the offset vanishes for very light or very strong damping, attaining a maximum that can be substantial depending on the strength of the HF excitation) for finite values of the damping. The analysis is focused on the differences between the classic results for weakly damped systems, and new effects for which the strong damping terms are responsible. The analysis is based on a slightly modified averaging technique, and includes an elementary example of an elliptically excited pendulum for illustration, alongside with a generalization to a broader class of strongly damped dynamical systems with HF excitation. As an application example, the nontrivial behavior of a classical optimally controlled nonlinear system is investigated, illustrating how HF excitation may cause the controller to leave the system in an unexpected equilibrium state, quite different from the setpoint. The effects can be interesting for specialists in control of mechanical systems and structures. However the obtained results are more general. Similar effects could be expected first of all for microsystems where damping forces are typically dominating over inertia forces.

General information
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering
Contributors: Fidlin, A., Thomsen, J. J.
Pages: 569-578
Publication date: 2008
Peer-reviewed: Yes

Publication information
Journal: International Journal of Non-Linear Mechanics
Volume: 43
Issue number: 7
ISSN (Print): 0020-7462
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 1.08 SNIP 1.537
Web of Science (2008): Indexed yes
Original language: English
Keywords: control, vibrations, effective properties
DOIs: 10.1016/j.ijnonlinmec.2008.02.002
Source: orbit
Source-ID: 206032
Research output: Contribution to journal – Annual report year: 2008 – Research – peer-review

Phase shift effects for fluid conveying pipes with non-ideal supports

Vibrations of a fluid-conveying pipe with non-ideal supports are investigated with respect to phase shift effects. A numerical Galerkin approach is developed for this general problem, and the use of it exemplified with a investigation of phase shift effects from rotational damping at supports of a simply supported pipe. It is found that asymmetric viscous rotational damping at supports gives rise to phase shifts along the pipe which cannot be distinguished from phase shift from mass flow. This is of interest, e.g., for the development and troubleshooting of Coriolis flow meters.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Dahl, J., Thomsen, J. J.
Number of pages: 2
Publication date: 2008

Host publication information
Title of host publication: Proceedings of XXII ICTAM, 25–29 August 2008, Adelaide, Australia
Place of publication: Adelaide, Australia
Publisher: University of Adelaide
Keywords: Fluid conveying pipes, Coriolis flowmeters, Phase shift
Using strong nonlinearity and high-frequency vibrations to control effective mechanical stiffness

High-frequency excitation (HFE) can be used to change the effective stiffness of an elastic structure, and related quantities such as resonance frequencies, wave speed, buckling loads, and equilibrium states. There are basically two ways to do this: By using parametrical HFE (with or without non-linearity), or by using external HFE along with strong nonlinearity. The first way has been examined for many different systems, and analytical predictions exist that has been repeatedly confirmed against numerical simulation and laboratory experiments. The current work contributes knowledge on the other way: Combining the method of direct separation of motions with results of a modified multiple scales approach, valid also for strong nonlinearity, the stiffening effect is predicted for a generic 1-dof system, and results are tested against numerical simulation and ((it is planned)) laboratory experiments.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Thomsen, J. J.
Number of pages: 9
Publication date: 2008

Using strong nonlinearity and high-frequency vibrations to control effective properties of discrete elastic waveguides

The aim of this article is to investigate how high-frequency (HF) excitation, combined with strong nonlinear elastic material behavior, influences the effective material or structural properties for low-frequency excitation and wave propagation. The HF effects are demonstrated on discrete linear spring-mass chains with non-linear inclusions. The presented analytical and numerical results suggest that the effective material properties can easily be altered by establishing finite amplitude HF standing waves in the non-linear regions of the chain.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics, VST Consulting Engineers Ltd.
Contributors: Lazarov, B. S., Thomsen, J. J., Snæland, S. O.
Number of pages: 6
Publication date: 2008

41560 Svingningslære: Opgaver & Løsninger

General information
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering
Contributors: Thomsen, J. J.
Publication date: 2007
**Nontrivial effects of high-frequency excitation for strongly damped mechanical systems**

Some nontrivial effects are investigated, which can occur if strongly damped mechanical systems are subjected to strong high-frequency (HF) excitation. The main result is a theoretical prediction, supported by numerical simulation, that for such systems the (quasi-)equilibrium states can change substantially with the level of damping. For example, a strongly damped pendulum, with a hinge vibrated at high frequency along an elliptical path with horizontal or vertical axis, will line up along a line offset from the vertical; the offset vanishes for very light or very strong damping, attaining a maximum that can be substantial (depending on the strength of the HF excitation) for finite values of the damping. The analysis is focused on the differences between the classic results for weakly damped systems, and new effects for which the strong damping terms are responsible. The analysis is based on a slightly modified averaging technique, and includes an elementary example of an elliptically excited pendulum for illustration, alongside with a generalization to a broader class of strongly damped dynamical systems with HF excitation. As an application example, the nontrivial behavior of a classical optimally controlled nonlinear system is investigated, illustrating how HF excitation may cause the controller to leave the system in an unexpected equilibrium state, quite different from the setpoint. The effects can be interesting for specialists in control of mechanical systems and structures. However the obtained results are more general. Similar effects could be expected first of all for microsystems where damping forces are typically dominating over inertia forces.

**Using nonlinearity and spatiotemporal property modulation to control effective structural properties: dynamic rods**

What are the effective properties of a generally nonlinear material or structure, whose local properties are modulated in both space and time? It has been suggested to use spatiotemporal modulation of structural properties to create materials and structures with adjustable effective properties, and to call these dynamic materials or spatiotemporal composites. Also, according to theoretical predictions, structural nonlinearity enhances the possibilities of achieving specific effective properties. For example, with an elastic rod having cubical elastic nonlinearities, it seems possible to control the effective propagation speed of long waves by varying the amplitude of a superimposed high-frequency standing wave. It should be possible to change most properties related to structural stiffness, energy dissipation, and equilibrium states this way, by exploiting the general effects of stiffening, biasing, and smoothening that characterize mechanically high-frequency excited structures. This work explores fundamental issues for spatiotemporally modulated nonlinear materials. First the effective stress-strain relation of a generally nonlinear material with a prescribed HF strain field is derived, discussed, and
exemplified. Then simple approximate analytical expressions are derived for the effective wave speed and natural frequencies for one-dimensional wave propagation in a nonlinear elastic rod, where the spatiotemporal modulation is imposed as a high-frequency standing wave, supposed to be given. Finally the more realistic case is briefly considered, where the HF standing wave is not given, but is a solution to given external HF input.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Thomsen, J. J., Blekhman, I. I.
Publication date: 2007

Host publication information
Title of host publication: Proceedings of COMPDYN 2007: ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering
Place of publication: Rethymno, Crete
Publisher: National Technical University of Athens
Keywords: vibrations, effective properties, high-frequency, elastic wave propagation

Bibliographical note
12 pages (CD-ROM)
Source: orbit
Source-ID: 206035
Research output: Chapter in Book/Report/Conference proceeding – Annual report year: 2007 – Research › peer-review

Computing effective properties of nonlinear structures exposed to strong high-frequency loading at multiple frequencies
Effects of strong high-frequency excitation at multiple frequencies (multi-HFE) are analyzed for a class of generally nonlinear systems. The effects are illustrated for a simple pendulum system with a vibrating support, and for a parametrically excited flexible beam. For the latter, theoretical predictions are supported by preliminary experimental results. The main effect of strong multi-HFE is to change the effective or apparent stiffness in a manner similar to that of mono-HFE, provided the HFE frequencies are well separated and non-resonant. Then the change in effective stiffness is proportional to the mean-square velocity of the excitation velocities, and the corresponding changes in equilibrium, equilibrium stability, and natural frequencies can be computed as for the mono-HFE case. When there are two or more close excitation frequencies, an additional contribution of slowly oscillating stiffness appears. This may cause strong parametrical resonance at conditions that might not appear obvious, i.e. when the difference in two HFE-frequencies is near twice an effective natural frequency of the system, which due to the HFE itself is shifted away from the natural frequency without HFE. Also, it is shown that strong multi-HFE can stabilize otherwise unstable equilibriums, but only if the frequencies are well separated; thus continuous broadband and random HFE does not have a stabilizing effect paralleling that of mono-HFE, or multi-HFE with non-close frequencies. The general results may be used to investigate general effects, or as a short cut to calculate effective properties for specific systems, or to calculate averaged equations of motion that may be much faster to simulate numerically.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Thomsen, J. J.
Pages: 1-20
Publication date: 2006

Host publication information
Title of host publication: CD-ROM proceedings of the III European Conference on Computational Mechanics
Place of publication: Lisbon
Keywords: high-frequency excitation, multiple frequency excitation, nonlinear structures, dynamic stiffening, effective properties
Source: orbit
Source-ID: 194126
Research output: Chapter in Book/Report/Conference proceeding – Annual report year: 2006 – Research › peer-review

Near-elastic vibro-impact analysis by discontinuous transformations and averaging: DCAMM Report 720
We show that near-elastic vibro-impact problems can be conveniently analyzed by a discontinuity-reducing transformation of variables, combined with an extended averaging procedure that allows small discontinuities. A general technique for this is presented, and illustrated by calculating transient or stationary motions for different harmonic oscillators with stops or clearances, and self-excited friction oscillators with stops or clearances First- and second-order analytical predictions are derived, and shown to agree to estimated accuracy with results of numerical simulation.
Vibrations and Stability: Solved Problems

Slow high-frequency effects in mechanics: problems, solutions, potentials
Strong high-frequency excitation (HFE) may change the 'slow' (i.e. effective or average) properties of mechanical systems, e.g. their stiffness, natural frequencies, equilibriums, equilibrium stability, and bifurcation paths. This tutorial describes three general HFE effects: Stiffening – an apparent change in the stiffness associated with an equilibrium; Biasing – a tendency for a system to move towards a particular state which does not exist or is unstable without HFE; and Smoothening – a tendency for discontinuities to be apparently smeared out by HFE. The effects and a method for analyzing them are introduced first in terms of simple physical examples, and then in generalized form for mathematical models covering broad classes of discrete and continuous mechanical systems. Several application examples are summarized. Three mathematical tools for analyzing HFE effects are described and compared: The Method of Direct Separation of Motions, the Method of Averaging, and the Method of Multiple Scales. The tutorial concludes by suggesting that more vibration experts, researchers and students should know about HFE effects, for the benefit not only of general vibration troubleshooting, but also for furthering the creation of innovative technical devices and processes utilizing HFE effects.
Slow high-frequency effects in mechanics: problems, solutions, potentials
Strong high-frequency excitation (HFE) may change the ‘slow’ (i.e. effective or average) properties of mechanical systems, e.g. their stiffness, natural frequencies, equilibriums, equilibrium stability, and bifurcation paths. This tutorial describes three general HFE effects: Stiffening – an apparent change in the stiffness associated with an equilibrium; Biasing – a tendency for a system to move towards a particular state which does not exist or is unstable without HFE; and Smoothening – a tendency for discontinuities to be apparently smeared out by HFE. The effects and a method for analyzing them are introduced first in terms of simple physical examples, and then in generalized form for mathematical models covering broad classes of discrete and continuous mechanical systems. Several application examples are summarized. Three mathematical tools for analyzing HFE effects are described and compared: The Method of Direct Separation of Motions, the Method of Averaging, and the Method of Multiple Scales. The tutorial concludes by suggesting that more vibration experts, researchers and students should know about HFE effects, for the benefit not only of general vibration troubleshooting, but also for furthering the creation of innovative technical devices and processes utilizing HFE effects.

General information
Publication status: Published
Organisations: Department of Mechanical Engineering, Solid Mechanics
Contributors: Thomsen, J. J.
Pages: 2799–2818
Publication date: 2005
Peer-reviewed: Yes

Publication information
Volume: 15
Issue number: 9
ISSN (Print): 0218-1274
Ratings:
Scopus rating (2005): SJR 0.655 SNIP 1.054
Web of Science (2005): Indexed yes
Original language: English
Keywords: High-frequency excitation, Fast vibrations, Direct separation of motions, Stiffening, Biasing, Smoothening, Vibrational control
DOIs:
10.1142/S0218127405013721
Source: orbit
Source-ID: 182377
Research output: Contribution to journal › Conference article – Annual report year: 2005 › Research › peer-review

Book review: ‘Theory of vibro-impact systems and applications’ by V.I. Babitsky

General information
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering
Contributors: Thomsen, J. J.
Pages: 317-318
Publication date: 2004
Peer-reviewed: No

Publication information
Journal: Journal of Vibration and Acoustics
Volume: 126
Issue number: 2
ISSN (Print): 1048-9002
Ratings:
Scopus rating (2004): SJR 1.008 SNIP 1.631
Web of Science (2004): Indexed yes
Original language: English
Source: orbit
Source-ID: 181409
Research output: Contribution to journal › Journal article – Annual report year: 2004 › Research
Discontinuous transformations and averaging for vibro-impact analysis
Certain vibro-impact problems can be conveniently solved by discontinuous transformations combined with averaging. We briefly outline the background for this, and then focus on illustrating the procedure for specific examples: A self-excited friction oscillator with one- or two-sided stops, and a particle on a vibrating plane. Vibro-impact systems are characterized by repeated collisions. Applications include devices to crush, grind, forge, drill, punch, tamp, pile, cut, and surface treat a variety of objects, and vibrating machinery or structures with slips and stops. Compared to the classical method of stitching (together non-impacting solution parts), the suggested procedure works even in the presence of additional nonlinearities, and provides analytical solutions without switching conditions. By contrast to the method of equivalent linearisation, it assumes a kinematic rather than kinetic impact formulation. Approximate methods in this area are necessary, and averaging with discontinuous transformations is believed to be a useful supplement.

General information
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering
Contributors: Thomsen, J. J., Fidlin, A.
Publication date: 2004

Host publication information
Title of host publication: Procedings of XXI Int. Congress of Theoretical and Applied Mechanics
Volume: 2 pages on CD
Publisher: XXI Int. Congress of Theoretical and Applied Mechanics
Source: orbit
Source-ID: 155679
Research output: Chapter in Book/Report/Conference proceeding – Article in proceedings – Annual report year: 2004
Research: peer-review

Non trivial effect of strong high-frequency excitation on a nonlinear controlled system
Nontrivial effects of high-frequency excitation on mechanical uncontrolled systems have been investigated intensively in the last decade. Some of these effects are usually used in controlled systems in form of dither to smoothen out undesired friction and hysteresis. However the level of damping due to control is usually high compared to uncontrolled systems. A standard optimal controller for a standard nonlinear system (a movable cart used to balance a pendulum vertically) is shown to exhibit pronounced bias error in presence of HF-excitation. The bias increases with increased excitation intensity, but it also increases with the increased control power. Analytic prediction for the bias shows, the interaction between fast excitation and strong damping terms in the control system to be the cause of the permanent control error. A "slow observer" ignoring fast motions is shown to be the simplest way to avoid the undesired bias in the considered particular system.

General information
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering
Contributors: Fidlin, A., Thomsen, J. J.
Number of pages: 2
Publication date: 2004

Host publication information
Title of host publication: XXI Int. Congress of Theoretical and Applied Mechanics
Place of publication: Warsaw
Publisher: IPPT PAN
Source: orbit
Source-ID: 155831
Research output: Chapter in Book/Report/Conference proceeding – Article in proceedings – Annual report year: 2004
Research: peer-review

Non-trivial effects of high-frequency excitation for pendulum type systems

General information
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering
Contributors: Jensen, J. S., Thomsen, J. J., Tcherniak, D. M.
Number of pages: 409
Pages: 73-137
Publication date: 2004
Analytical approximations for stick-slip vibration amplitudes

The classical "mass-on-moving-belt" model for describing friction-induced vibrations is considered, with a friction law describing friction forces that first decreases and then increases smoothly with relative interface speed. Approximate analytical expressions are derived for the conditions, the amplitudes, and the base frequencies of friction-induced stick-slip and pure-slip oscillations. For stick-slip oscillations, this is accomplished by using perturbation analysis for the finite time interval of the stick phase, which is linked to the subsequent slip phase through conditions of continuity and periodicity. The results are illustrated and tested by time-series, phase plots and amplitude response diagrams, which compare very favorably with results obtained by numerical simulation of the equation of motion, as long as the difference in static and kinetic friction is not too large.
Dynamic Effects of Nonlinearity and Fast Vibrations: Stiffening, Biasing, Smoothening, Chaos

Strange effects of strong high-frequency excitation
Three general effects of mechanical high-frequency excitation (HFE) are described: Stiffening - an apparent change in the stiffness associated with an equilibrium; Biasing - a tendency for a system to move towards a particular state which does not exist or is unstable without HFE; and Smoothening - a tendency for discontinuities to be apparently smeared out by HFE. Studies of specific physical systems as well as more general models are described.

Theories and experiments on the stiffening effect of high-frequency excitation for continuous elastic systems
One effect of strong mechanical high-frequency excitation may be to apparently "stiffen" a structure, a well-described phenomenon for discrete systems. The present study provides theoretical and experimental results on this effect for continuous elastic structures. A laboratory experiment is set up for demonstrating and measuring the stiffening effect in a simple setting, in the form of a horizontal piano string subjected to longitudinal high-frequency excitation at the clamped
base and free at the other end. A simplest possible theoretical model is set up and analyzed using a hierarchy of three approximating theories, each providing valuable insight. One of these is capable of predicting the vertical string lift due to stiffening in terms of simple expressions, with results that agree very well with experimental measurements for a wide range of conditions. It appears that resonance effects cannot be ignored, as was done in a few related studies unless the system has very low modal density or heavy damping; thus first-order consideration to resonance effects is included. Using the specific example with experimental support to put confidence on the proposed theory, expressions for predicting the stiffening effect for a more general class of continuous systems in differential operator form are also provided.
Post-critical behavior of Beck's column with a tip mass

This study examines how a tip mass with rotary inertia affects the stability of a follower-loaded cantilevered column. Using nonlinear modeling and perturbation analysis, expressions are set up for determining the stability of the straight column and the amplitude of post-critical flutter oscillations. Bifurcation diagrams are given, showing how the vibration amplitude changes with follower load and other parameters. These results agree closely with numerical simulation. It is found that sufficiently large values of tip mass rotary inertia can change the primary bifurcation from supercritical into subcritical. This can imply very large motions for follower loads just beyond critical, contrasting the finite amplitude motions accompanying supercritical bifurcations. Also, the straight column may be destabilized by a sufficiently strong disturbance at loads far below the value of critical load predicted by linear theory. A similar change in bifurcation is found to occur with increased external (as compared to internal) damping, and with a shortening in column length. These effects are not revealed by linear modeling and analysis, which may consequently fail to predict even qualitatively the real critical load for a column with tip mass.

Some general effects of strong high-frequency excitation: stiffening, biasing, and smoothening

Mechanical high-frequency (HF) excitation provides a working principle behind many industrial and natural applications and phenomena. This paper concerns three particular effects of HF excitation, that may change the apparent characteristics of mechanical systems: 1) stiffening, by which the apparent linear stiffness associated with an equilibrium is changed, along with derived quantities such as stability and natural frequencies; 2) Biasing, by which the system is biased towards a particular state, static or dynamic, which does not exist or is unstable in the absence of the HF excitation; and 3) smoothening, referring to a tendency for discontinuities to be effectively "smeread out" by HF excitation. Illustrating first these effects for a few specific systems, analytical results are provided that quantify them for a quite general class of mechanical systems. This class covers systems that can be modeled by a finite number of second order ordinary differential equations, generally nonlinear, with periodically oscillating excitation terms of high frequency and small amplitude. The results should be useful for understanding the effects in question in a broader perspective than is possible with specific systems, for calculating effects for specific systems using well-defined formulas, and for possibly designing systems that display prescribed characteristics in the presence of HF excitation.
Vibrations and Stability - Order & Chaos, Solved Problems

Chelomei’s pendulum explained
Chelomei’s pendulum has a sliding disc on its rod, and is mounted on a support that vibrates vertically with small amplitude and high frequency. In 1982, V. N. Chelomei demonstrated experimentally that a configuration can be stable where the pendulum points against gravity, and the disc ‘floats’ on the rod. This phenomenon has never been satisfactorily explained. The present work considers why and where the disc floats. It suggests that the phenomenon is caused by resonant flexural rod vibrations, which are excited through small symmetry-breaking imperfections, such as a small deviation from perfectly vertical excitation. This hypothesis is supported by laboratory experiments, and by perturbation analysis and numerical analysis of a new mathematical three-degree-of-freedom model of the system. Simple analytical expressions for the prediction of stable states of the system are set up, providing frequency responses that agree closely with numerical simulation, and agree qualitatively with experimental observations.

Chelomei’s pendulum explained
Chelomei’s pendulum has a sliding disc on its rod, and is mounted on a support that vibrates vertically with small amplitude and high frequency. In 1982, V. N. Chelomei demonstrated experimentally that a configuration can be stable where the pendulum points against gravity, and the disc ‘floats’ on the rod. This phenomenon has never been satisfactorily explained. The present work considers why and where the disc floats. It suggests that the phenomenon is caused by resonant flexural rod vibrations, which are excited through small symmetry-breaking imperfections, such as a small deviation from perfectly vertical excitation. This hypothesis is supported by laboratory experiments, and by perturbation analysis and numerical analysis of a new mathematical three-degree-of-freedom model of the system. Simple analytical expressions for the prediction of stable states of the system are set up, providing frequency responses that agree closely with numerical simulation, and agree qualitatively with experimental observations.

General information
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering
Contributors: Thomsen, J. J.
Publication date: 2002
Predicting vibration-induced displacement for a resonant friction slider

A mathematical model is set up to quantify vibration-induced motions of a slider, sandwiched between friction layers with different coefficients of friction, and equipped with an imbedded resonator that oscillates at high frequency and small amplitude. This model is highly nonlinear, involving non-smooth functions with strong harmonic excitation terms. The method of averaging is extended to hold for systems of this class, and used to derive approximate expressions for predicting average velocities of the slider. These expressions are shown to produce results that agree very well with numerical integration of the full equations of motion. The expressions are used to estimate and explain the influence of system parameters.

General information
Publication status: Published
Organisations: Solid Mechanics, Department of Mechanical Engineering
Contributors: Fidlin, A., Thomsen, J. J.
Pages: pp. 155-166
Publication date: 2001
Peer-reviewed: Yes

Publication information
Volume: Vol. 20
Issue number: 1
ISSN (Print): 0997-7538
Ratings:
Scopus rating (2001): SJR 1.055 SNIP 1.259
Web of Science (2001): Indexed yes
Original language: English
Source: orbit
Source-ID: 64099

Stiffening effects of high-frequency excitation: experiments for an axially loaded beam

General information
Publication status: Published
Organisations: Department of Solid Mechanics
Contributors: Jensen, J. S., Tcherniak, D., Thomsen, J. J.
Pages: 397-402
Publication date: 2000
Peer-reviewed: Yes

Publication information
Journal: Journal of Applied Mechanics
Volume: 67
Issue number: 2
ISSN (Print): 0021-8936
Ratings:
Scopus rating (2000): SJR 1.713 SNIP 1.591
Web of Science (2000): Indexed yes
Original language: English
Source: orbit
Source-ID: 177241

Vejledning til Øvelser i Eksperimentel Faststofmekanik

General information
Publication status: Published
Organisations: Department of Solid Mechanics
Contributors: Nielsen, A. G., Thomsen, J. J.
Number of pages: 53
Vibration-induced displacement using high-frequency resonators and friction layers

General information
Publication status: Published
Organisations: Department of Solid Mechanics
Contributors: Thomsen, J. J.
Pages: 237-247
Publication date: 2000

Host publication information
Title of host publication: Proceedings of the IUTAM / IFToMM Symposium on Synthesis of nonlinear Dynamical Systems, Riga, 1998
Place of publication: Dordrecht
Publisher: Kluwer Academic Press
Source-ID: 170167

Vibrations and Stability - Order & Chaos, Solved Problems

General information
Publication status: Published
Organisations: Department of Solid Mechanics
Contributors: Thomsen, J. J.
Number of pages: 84
Publication date: 2000

Publication information
Original language: English
Source: orbit
Source-ID: 170026

Non-Trivial Effects of Fast Harmonic Excitation: Experiments for an Axially Loaded Beam

General information
Publication status: Published
Organisations: Department of Solid Mechanics
Contributors: Jensen, J. S., Tcherniak, D., Thomsen, J. J.
Publication date: 1999

Publication information
Original language: Danish
Source: orbit
Source-ID: 173778

Using Fast Vibrations to Quench Friction-induced Oscillations
This work examines how friction-induced self-excited oscillations are affected by high-frequency external excitation. Simple analytical approximations are derived for predicting the occurrence of self-excited oscillations for the traditional mass-on-moving-belt model – with and without high-frequency excitation. It appears that high-frequency excitation can effectively cancel the negative slope in the friction-velocity relationship, and may thus prevent self-excited oscillations. To accomplish this it is sufficient that the (nondimensional) product of excitation amplitude and frequency exceeds the velocity corresponding to the minimum kinetic coefficient of friction. Simple expressions are given also for predicting the excitation necessary for quenching self-excited oscillations at or below a specified belt velocity. These and other results
Contribute to the general understanding of how friction properties may change under the action of fast vibrations.

**General information**
Publication status: Published
Organisations: Department of Solid Mechanics
Contributors: Thomsen, J. J.
Pages: 1079-1102
Publication date: 1999
Peer-reviewed: Yes

**Publication information**
Journal: Journal of Sound and Vibration
Volume: 228
Issue number: 5
ISSN (Print): 0022-460X
Ratings:
Scopus rating (1999): SJR 1.077 SNIP 1.184
Original language: English
Source: orbit
Source-ID: 173779
Research output: Contribution to journal › Journal article – Annual report year: 1999 › Research › peer-review

**Videregaaende Databehandling (M) - Noter og Opgaver**

**General information**
Publication status: Published
Organisations: Department of Solid Mechanics
Contributors: Thomsen, J. J., Hansen, J. M.
Number of pages: 78
Publication date: 1999

**Publication information**
Original language: Danish
Source: orbit
Source-ID: 167353
Research output: Book/Report › Book – Annual report year: 1999 › Research › peer-review

**Nonlinear Dynamic Interactions: Tools, Examples, Cases**

**General information**
Publication status: Published
Organisations: Department of Solid Mechanics
Contributors: Thomsen, J. J.
Number of pages: 120
Publication date: 1998

**Publication information**
Original language: English
Source: orbit
Source-ID: 167351
Research output: Book/Report › Book – Annual report year: 1998 › Research › peer-review

**Slow effects of fast harmonic excitation for elastic structures**

High-frequency excitation may affect the 'slow' behavior of a dynamical system. For example, equilibria may move, disappear, or gain or lose stability. We consider such slow effects of fast excitation for a simple mechanical system that incorporates features of many engineering structures. The study is intended to contribute to the general understanding of periodically excited linear and nonlinear systems, as well as to the current attempts to utilize high-frequency excitation for altering the low-frequency properties of structures.

**General information**
Publication status: Published
Organisations: Department of Solid Mechanics, Saint Petersburg State Marine Technical University
Contributors: Tcherniak, D., Thomsen, J. J.
Pages: 227-246
Vibration induced sliding: theory and experiment for a beam with a spring-loaded mass

The study sets up a simple model for predicting vibration induced sliding of mass, and provides quantitative experimental evidence for the validity of the model. The results lend confidence to recent theoretical developments on using vibration induced sliding for passive vibration damping, and contributes to a further understanding of this nonlinear phenomenon. A mathematical model is set up to describe vibration induced sliding for a base-excited cantilever beam with a spring-loaded pointmass. Approximations simplify the model into two nonlinear ordinary differential equations, describing motions of the system at near-resonant excitation of a single beam mode. This simplified model is studied numerically and analytically, and tested against laboratory experiments. The experiments provide evidence that the simplified mathematical model retains those features of the real system that are necessary for making useful predictions of transient and stationary first-mode response.

General information
Publication status: Published
Organisations: Department of Solid Mechanics
Contributors: Miranda, E., Thomsen, J. J.
Pages: 167-186
Publication date: 1998
Peer-reviewed: Yes

Vibration Induced Sliding: Theory and Experiment for a Beam with a Spring-Loaded Mass

General information
Publication status: Published
Organisations: Department of Solid Mechanics, Technical University of Denmark
Contributors: Miranda, E., Thomsen, J. J.
Publication date: 1997

Vibrations and Stability, Order and Chaos

General information
Nonlinear Dynamic Interactions: Tools, Examples, Cases

Vibration induced sliding of mass: non-trivial effects of rotatory inertia

Vibrations and Stability - Order & Chaos, Solved Problems

Vibration suppression using self-arranging mass: effects of
Chaotic Dynamics of the Partially Follower-Loaded Elastic Double Pendulum

The non-linear dynamics of the elastically restrained double pendulum, with non-conservative follower-type loading and linear damping, is re-examined with specific reference to the occurrence of chaotic motion. A local non-linear perturbation analysis is performed, showing that in three distinct regions of loading parameter space, small initial disturbances will result in, respectively, (1) static equilibrium solutions, (2) stable periodic motion, and (3) initially large changes in amplitude due to a destabilizing effect of both linear and non-linear forces. A global numerical analysis confirms the theoretical findings for regions (1) and (2), and shows that in region (3) almost all solutions are chaotic. It is suggested that chaos is triggered by a bifurcating cascade of large amplitude stable and unstable equilibrium points, which may be explored by orbits only when the zero-solution is destabilized by both linear and non-linear forces. Although heuristically based, this may be used as a practical and rather accurate predictive criterion for chaos to appear in the specific system.

Copyright © 1995 Academic Press. All rights reserved.

Chaotic Vibrations of Non-shallow Arches
Quality Control of Composite Materials by Neural Network Analysis of Ultrasonic Power-Spectra

General information
Publication status: Published
Organisations: Department of Solid Mechanics
Contributors: Thomsen, J. J.
Pages: 594-600
Publication date: 1991
Peer-reviewed: Yes

Publication information
Journal: Materials Evaluation
Issue number: May
ISSN (Print): 0025-5327
Original language: English
Electronic versions:
Quality_Control_of_Composite_Materials.pdf
Source: PublicationPreSubmission
Source-ID: 98935167
Research output: Contribution to journal › Journal article – Annual report year: 1991 › Research › peer-review

Modelling Human Tibia Structural Vibrations

General information
Publication status: Published
Organisations: Department of Solid Mechanics
Contributors: Thomsen, J. J.
Pages: 215-228
Publication date: 1990
Peer-reviewed: Yes

Publication information
Journal: Journal of Biomechanics
Volume: 23
Issue number: 3
ISSN (Print): 0021-9290
Original language: English
Electronic versions:
Thomsen_1990_ModellingHumanTibiaStructuralVibrations.pdf
Source: PublicationPreSubmission
Source-ID: 98935158
Research output: Contribution to journal › Journal article – Annual report year: 1990 › Research › peer-review