Vibration Protection Systems

Design and deploy advanced vibration protection systems based on elastic composites under postbuckling with this essential reference. Providing new insight into vibration isolation, methods for designing vibration protection systems with negative and quasi-zero stiffness are formulated, explained, and demonstrated in practice. All key steps of the system design are covered, including the type and number synthesis, modeling and studying of stress-strain state under postbuckling of elastic composite designs, chaotic dynamics and stability conditions, real-time dimensioning, and active parametric and motion control. In addition to coverage of underlying theory, discussion of uses in helicopters, buses, railroad vehicles, construction equipment, and agricultural machinery is included. This book is an excellent reference for researchers and practicing engineers, as well as a tutorial for university students and professors with an interest in the study, development, and application of alternative methods of vibration protection.

Chang-Myung Lee is Professor in the Department of Mechanical and Aerospace Engineering at the University of Ulsan.

Vladimir Nicholas Goverdovskiy is Foreign Researcher at the University of Ulsan.

Vibration Protection Systems

Negative and Quasi-Zero Stiffness

CHANG-MYUNG LEE
University of Ulsan

VLADIMIR NICHOLAS GOVERDOVSKIY
University of Ulsan

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781108834957
DOI: 10.1017/9781108874540

First published 2021

Printed in the United Kingdom by TJ Books Limited, Padstow Cornwall

A catalogue record for this publication is available from the British Library.

ISBN 978-1-108-83495-7 Hardback

Contents

Preface

This book is aimed at the serious practitioner, as well as the university student or professor, interested in some new and unusual methods of vibration protection. It may also serve as a useful basis to the researcher in one or another of the various science and technology disciplines. Vibration measurement and protection and dramatic updating of the preconceived ideas and phenomenological models in this area are good examples where for each item a completely new subject has grown. This book is for development engineers who are seeking advanced design solutions in automotive, high-speed railroad, and aerospace engineering based on the new platforms so as to create distinct and competitive products, but for reasonable cost, and for all who want but do not know how, or who have desperately wanted, to get rid of the vibrations that interfere with implementation of their promising technical solutions.

The experts in the area of vibration engineering and vibration protection know well that methods of vibration protection can be divided into four groups. These are structural vibration protection, vibration absorbing, damping, and vibration isolation. However, such a grouping is tentative enough since the methods complement each other to the extent determined by the complexity and specificity of the vibration problem being solved. Mainly, this book is about methods of vibration isolation, which are perhaps the least developed, however, most capable of becoming most promising and effective, regardless of the type of vibration protection object.

More than 50 years have passed since a great practical interest appeared in the vibration protection systems with sign-changing stiffness variable from negative to quasi-zero values. Over the next few decades, a rapid but mostly heuristic development of such systems has continued. The code name of such systems has undergone many changes. Little has changed since then concerning the origins of the subject and its phenomenon. As a result, many of the theoretical and practical problems needing to be solved in developing such systems have stood over or survived almost intact.

At the same time, there has been great development in the variety of vibration-sensitive equipment and mechanisms in land vehicles (heavy trucks, buses, etc.); high-speed, long-distance railroad systems under intensive development (rolling stock and infrastructural objects); manned (e.g., helicopters) and unmanned (e.g., nanosats, drones) aircrafts; and many other transport machines. These are also the measuring instruments for micro- and nanoelectronics, optics, medical, and bioengineering areas. Besides, these are extremely complex and expensive (at the cost of hundreds of millions to a few billion USD each), high-energy systems, such as the rings of synchrotron radiation and future colliders for basic research and many high-tech applications.

This and other next-generation equipment, machines, and technology have become largely unrecognizable as they are developed based on new scientific knowledge and engineering materials. All are in urgent need of vibration protection, especially in the infra-low-frequency range, including near-zero values, since even the most advanced of the existing vibration protection systems, such as active pneumatics, are powerless in these vibrations. For instance, improvement of the capacity (emittance and offset) of beam accelerators (in synchrotron rings and future colliders) depends no longer on improving the design and tightening the tolerances. However, the infra-low-frequency structural vibrations amplified by external technogenetic and seismic vibration activity became a critical limiting factor in developing the systems.

However, humans suffer most from the infra-low-frequency vibrations, which crucially affect their physical and mental health as well as work activity, especially if exposure time to the vibrations is long enough. Therefore, the human operators and passengers of all types of vehicles, people in residential areas, and workers within enterprises located near transport systems and hubs are the main beneficiaries of infra-low-frequency vibration protection.

Many papers have been published in the journals and proceedings of scientific conferences concerning particular cases of the design and study of vibration protection systems with negative and quasi-zero stiffness. However, this book, for the first time, embraces key methods for designing and developing systems and for the logical interrelation of these methods, which has not been written previously. It is important because of the tremendous growth in the subject both in the relevant theory but also in the practice of the subject and due to the ever-widening range of research and industrial applications.

It has to be admitted that the subject has become so large that one cannot hope to cover everything in a single book. Therefore, it would be foolish to pretend that this book could cover all subjects in development of such unusual vibration protection systems. Nevertheless, the methods and design sampling of the systems presented in the book allow making the design process more conscious, more science based, and less heuristic.

The book consists of 10 chapters, in which the problem and subjects of the research are presented, as well as the solutions to what is poorly elucidated or completely absent in existing research literature for the design and study of vibration protection systems with negative and quasi-zero stiffness. Besides, the results presented in the book allow avoiding some obstacles in designing and in the practical use of vibration protection systems with negative and quasi-zero stiffness, as well as illustrating the multiple superiority and promise of such systems compared to the best of the known vibration protection systems designed by other methods.

In Chapter 1, we briefly characterize the common problem – the infra- and low-frequency vibrations, which are the most harmful and dangerous for humans and many types of machines and equipment. Here also the most common vibration protection systems among conventional ones are presented. Besides, the effectiveness of such systems in transport vehicles is illustrated to show that, in many cases, it lacks significantly the safety and ride comfort requirements for humans inside the moving vehicles, as well as the people outside these vehicles but living near a transport infrastructure.

Chapter 2 presents the most successful, among the widely known, vibration protection systems with negative and quasi-zero stiffness and examples of their experimental and industrial applications. A generic model of the systems with sign-changing stiffness and a set of key parametric relations are formulated. By these formulations, it is illustrated why the known mechanisms and systems occupy an undeserved modest place among existing types of vibration protection systems with negative and quasi-zero stiffness, despite its seeming potential and greater superiority in efficiency than are seen in conventional ones.

In Chapter 3 we theoretically evolve the models started in Chapter 2. Furthermore, we develop in detail a methodology for modeling and studying the stress-strain state of geometrically nonlinear elastic structures, mechanisms, and systems under post-buckling in large. This methodology may be considered as a genesis for designing a great number of the systems with negative and quasi-zero stiffness regardless of design features. The methodology is based on a consistent theory of thin shells and makes it possible to formulate, using the finite element method, the numerical procedures for online design of structures and mechanisms with negative and quasi-zero stiffness. The methodology and procedures are more advanced and go far beyond the capabilities of well-known theoretical approaches; however, they became easy to use for optimal online computation of key parameters and functions for designing such structures, mechanisms, and systems.

Chapter 4 concerns the structural design of the mechanisms that could reveal negative and quasi-zero stiffness. Perhaps there are no other books that would address the issues of structural design of such mechanisms. Missing this step of the design is a main reason why the known mechanisms and systems do not operate as well as they could. We formulated and validated a method of the type and number synthesis of such systems and their structural members. The method provides an intelligent structural design and predicts the performance of the vibration protection systems, being equipped with mechanisms of negative and quasi-zero stiffness. The method follows the principle "do no harm" as well as numerically, not heuristically, showing how to improve the vibration protection of machines and equipment at early stages of design.

Chapters 5–7 are devoted to poorly studied problems of dynamics of passive and active systems with negative and quasi-zero stiffness. From Chapter 5, it may be appropriate to know and bear in mind that such systems can reveal chaotic and thus unpredictable vibration motion. Therefore, we propose an algorithm for diagnostics to measure chaos and predict conditions for nonchaotic vibration motion of these systems. First, some design parameters and motion effects can be unpredictable and would be likely to remain if one did not take into account this specific dynamic behavior. Second, it is no matter how much we improve the models to predict the capabilities of a final system, which is certainly a consequence of advances in computing technology. However, we try to show how to foresee and avoid chaos at early stages of system design.

Chapter 6 explains that the vibration protection systems with extremely small (quasi-zero) stiffness can be most effective in the infra-frequency range if the system damping is controllable to certain small values, however, avoiding the loss of system stability. This is utterly important for vibration protection of humans and some high-precision instrument and machinery generating near-zero frequency vibrations. Active parametric and motion control is required in such modes of system operation. However, in Chapter 7, we show that the motion control of systems with negative and quasi-zero stiffness is different and can be significantly simpler in comparison to the methods of active control for conventional vibration protection systems.

Chapter 8 is devoted to the methods of experimental modeling and study of systems with negative and quasi-zero stiffness. We consider general methods for the study of statics and dynamics in combination with original approaches and facilities to investigate features of the behavior of such systems. Reliability of the methods is determined by industrial and commercial pressure. These lead us toward greater use of simulation models and test planning so that the tests we do conduct can provide quality of processing and a reasonable selection of the measured data required to solve research tasks within a short time.

Chapters 9 and 10 concern the preparation and fulfillment of developmental testing in the field and practical use of vibration protection systems. We investigated the operation of new systems in harmony with conventional ones. Such harmony can lead to a drastic rise in the quality of vibration protection in existing and next-generation machines and equipment where the problem of vibration protection remains unsolved. This concerns all types of land vehicles, construction equipment, helicopters, high-speed railroad systems, and many other vehicles.

In an afterword to Chapter 10, we demonstrate how much more progress can be achieved in vibration protection when using systems with negative and quasi-zero stiffness with brand-new structural composites. Systems with negative and quasi-zero stiffness can be proved to be the most effective and promising to meet and multiply outdo the vibration protection standards. In any case, we try to demonstrate that the new systems are ready not only for use in advanced hybrids with existing systems but also for replacing them in many applications as applied to mechanical engineering, automotive, aerospace, and other prospective technology. Vibration protection systems with negative and quasi-zero stiffness, it seems, could have a secure and long-term future, justifying the investment that might be made in certain areas, and not only those treated within this book.

Noting that a number of relevant papers have appeared in recent years, it should also be noted that in the book, at the end of each chapter, we have sought to provide the reader with a judicious selection of references that is not overwhelming. Of course, such a selection is relatively subjective. However, the concerned reader can find literature reviews in many different areas covered by this book in some of the references cited.

Acknowledgments

This book appears as the work of two authors; however, in fact, it contains the contributions of a great many colleagues who have accompanied the authors along various parts of the road that its contents describe.

The book appeared as the result of a set of papers prepared and published for some of our early theoretical and experimental studies in vibration protection. Over a few years, several new aspects of the problem were developed and refined by the authors. The book is, to a large extent, the result of that development of activity of comprehensive research, together with developing and practicing the new and very specific technology of vibration protection, as well as in the parallel teaching of university students, which it describes. As a result, there are some groups of people who have contributed to this book. The first group comprises those who have initially formed our scientific worldview in this field of science and technology. The second group includes all our colleagues who have participated in various ways in the research, who have played such an important role in the development of the subject, as well as in its practice in a wide range of industries, and whose names are listed in the references of the book. The third group includes mostly young people who have worked with us in the development of the samples and testing of the subject – mostly research students and research assistants, as well as production workers, engineers, designers, technologists, test drivers, and pilots. There are in addition to these named helpers a number of other people whose support in all manner of ways has been the deciding factor in the long-running debate as to whether the book would appear. We acknowledge the support of each individually. Each has played a critical role in providing us with the space and support we needed to get to this goal. Clearly, their contributions are very significant, for they constitute most of the currently used methods.

These important groups of participants include, in the first place, our mentors and founders of a world-famous research school on vibration science and technology – Professors Peter M. Alabuzhev and George S. Migirenko. They encouraged us to undertake a more than 30-year voyage among theoretical and experimental research in this field that was so engaging and promising.

Of blessed memory are Professor George G. Furin, who had an indelible impression on our scientific worldview and gave invaluable assistance in developing new materials urgently needed to improve unusual vibration protection systems, and Dr. Anatoly I. Temnikov, who developed and promoted in practice many of original algorithms for system design and active control.

Many colleagues have helped in running our research; significant among these have been Professors Igor S. Nikyphorov, Vladimir A. Aksenov, Dmitry D. Moldavskiy, Peter I. Ostromenskiy, and Sergey V. Eliseev, as well as Drs. Andrey H. Bogachenkov and Leonid I. Kim. They and other scientists have played a major role in making up our personalities and helped in developing different parts of our theoretical and experimental methods.

We must record our deep thanks to the University of Ulsan (Korea) for many years of scientific, technological, and material assistance for our research. We also must record our deep thanks to the Russian Science Foundation for support (research grant 17-19-01389) and encouragement that helped us in developing the book and supplementing it with new research results, and then in presenting the problem of vibration protection and its very promising solution for the future.

We also deeply thank for support and incredible patience those at Cambridge University Press who helped to realize this publication and who encouraged and indulged us to the point where this book was completed within a relatively short period of time.

Glossary

effective segment or area (e.a.) of control of negative (or quasi-zero) stiffness. A range of stiffness control due to either an inner property of a parametric element, structure, mechanism or inserting into a vibration protection system's kinematic structure an external (redundant) structural or parametric element or mechanism able to produce the negative (or quasi-zero) stiffness.

finite element (FE). A finite number of discrete elements of a system, interconnected at discrete nodes and used to model a physical system.

function-generating mechanism (FGM). A system of structural and parametric elements whose relative motion causes a certain motion of output structural element according to a specified motion of input structural element.

infra- and low frequencies. Vibration frequency range, $f = 1-100$ Hz.

infra-frequencies. Vibration frequency range, $f \leq 10$ Hz.

near-zero frequencies. Vibration frequency range, f = 0–1 Hz.

parametric element. An element of a vibration protection system considered as a deformable body in the vibration protection system motion.

parametric element with sign-changing stiffness. A deformable body or structure whose stiffness can be positive in translation, $\mathrm{d}F/\mathrm{d}z > 0$, or rotation, $\mathrm{d}T/\mathrm{d}\varphi > 0$, close to zero (quasi-zero), $\mathrm{d}F/\mathrm{d}z \approx 0$ or $\mathrm{d}T/\mathrm{d}\varphi \approx 0$, or negative, $\mathrm{d}F/\mathrm{d}z < 0$ or $\mathrm{d}T/\mathrm{d}\varphi < 0$, depending on the preloading and holding of the element at one of the states of strain, where F or T is a force or torque applied to the element in the direction of its linear, z, or angular, φ, displacement.

parametric (local) degrees of freedom. Mobility of a vibration protection system due to relative motion or deformation of parametric elements.

postbuckling. Effect of instability and subsequent local or global displacement of structural elements or elastic nonlinear deformation of a parametric (elastic) element designed e.g., in the form of a rod, plate, shell or other thin-walled structure.

postbuckling in large. The effect in a given direction of the vibration protection system motion is compatible with the dimensions of a system of movable joined structural elements or parametric (elastic) elements. *See* postbuckling

postbuckling in small. The effect in a given direction of the vibration protection system motion is negligibly small in comparison with the dimensions of a system of movable joined structural elements or parametric (elastic) elements. *See* postbuckling

redundant kinematic chain (RKC). Structural elements connected by joints (kinematic pairs) designed to movably join the redundant mechanism and a vibration protection mechanism.

redundant mechanism (RM). Removal of such a redundant mechanism from the kinematic structure of a vibration protection system does not result in performance failure of the vibration protection system of an initial structure (before inserting the redundant mechanism).

redundant structural or parametric element. Removal of such an element from the kinematic structure of a vibration protection mechanism does not result in performance failure of the mechanism of an initial structure (before inserting the element).

structural element. An element of a vibration protection system considered as a solid body in the vibration protection system motion.

structural (generalized) degree of freedom. Mobility of a vibration protection system due to the relative motion of structural elements.

vibration isolation. The method of vibration protection that consists in placing a vibration protection mechanism (vibration isolator) between a vibration source and an object being protected to separate the frequency spectra of the source and the natural frequencies of a vibration protection system.

vibration protection mechanism. A system of interacting structural elements of a function-generating mechanism, parametric (elastic and damping) elements, and the elements of passive or active parametric and position control.

vibration protection system (VPS). A system of interacting structural members including a source of kinematic (external) and/or dynamic (structural) vibrations affecting the system at certain attachment points, a vibration protection mechanism (seat suspension, cabin or engine mount, vibration isolators for instrumentation, etc.), and an object being protected (a human operator, a passenger, or equipment).