Walter Lacarbonara
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Jun Ma · J. A. Tenreiro Machado
Gabor Stepan *Editors*

Nonlinear Dynamics of Structures, Systems and Devices

Proceedings of the First International Nonlinear Dynamics Conference (NODYCON 2019), Volume I

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ISBN 978-3-030-34712-3 ISBN 978-3-030-34713-0 (eBook)
https://doi.org/10.1007/978-3-030-34713-0

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The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

This volume is part of three volumes collecting the *Proceedings of the First International Nonlinear Dynamics Conference (NODYCON 2019)* held in Rome, February 17–20, 2019. NODYCON was launched to foster the tradition of the conference series originally established by Prof. Ali H. Nayfeh in 1986 at Virginia Polytechnic Institute and State University (Virginia Tech), Blacksburg, VA, USA, as the Nonlinear Vibrations, Stability, and Dynamics of Structures Conference. With the passing in 2017 of Prof. Nayfeh, who was also the founder of the Springer journal *Nonlinear Dynamics* in 1990, NODYCON 2019 was organized as a collective tribute of the community to Prof. Nayfeh for being one of the most influential leaders of nonlinear dynamics. NODYCON 2019 was also established to look to and dream about the future. The call for papers attracted contributions dealing with established nonlinear dynamics research topics as well as with the latest trends and developments. At the same time, to reflect the rich spectrum of topics covered by the journal *Nonlinear Dynamics*, the call included diverse and multidisciplinary topics, to mention a few, multi-scale dynamics, experimental dynamics, dynamics of structures/industrial machines/equipment/facilities, dynamics of adaptive, multifunctional, metamaterial structures, dynamics of composite/nanocomposite structures, reduced-order modeling, nonsmooth dynamics, fractional-order system dynamics, nonlinear interactions and parametric vibrations, computational techniques, nonlinear system identification, dynamics of NEMS/MEMS/nanomaterials, multibody dynamics, fluid/structure interaction, influence of nonlinearities on vibration control systems, human–machine interaction, nonlinear wave propagation in discrete and continuous media, chaotic map-based cryptography, ecosystem dynamics, social media dynamics, complexity in engineering, and network dynamics.

For NODYCON 2019, the organizers received 450 two-page abstracts and based on 467 reviews from the Program Committee, the Steering and Advisory Committees, and external reviewers, 391 papers and 17 posters were accepted, published in the Book of Abstracts (NODYS Publications, Rome, ISBN 978-88-944229-0-0), and presented by nearly 400 participants from 68 countries. The diverse topics covered by the papers were organized along four major themes to organize the technical sessions:

(a) Concepts and methods in nonlinear dynamics
(b) Nonlinear dynamics of mechanical and structural systems
(c) Nonlinear dynamics and control
(d) Recent trends in nonlinear dynamics

The authors of a selection of approximately 60 papers were invited to publish in the Special Issue of *Nonlinear Dynamics* entitled "NODYCON 2019 First International Nonlinear Dynamics Conference." Over 200 full papers were submitted to the *Proceedings of the First International Nonlinear Dynamics Conference* (NODYCON 2019) and only 121 of them were accepted. These papers have been collected into three volumes, which are listed below together with a sub-topical organization.

Volume 1: Nonlinear Dynamics of Structures, Systems, and Devices

(a) Methods for nonlinear dynamics
(b) Bifurcations and nonsmooth systems
(c) Nonlinear phenomena in mechanical systems and structures
(d) Experimental dynamics, system identification and monitoring
(e) Fluid–structure interaction, multibody system dynamics
(f) Turning processes, rotating systems, and systems with time delays

Volume 2: Nonlinear Dynamics and Control

(g) Vibration absorbers and isolators
(h) Control of nonlinear systems
(i) Sensors and actuators
(j) Network synchronization

Volume 3: New Trends in Nonlinear Dynamics

(k) Smart materials, metamaterials, composite and nanocomposite materials, and structures
(l) MEMS/NEMS and energy harvesters
(m) Nonlinear phenomena in bio- and ecosystem dynamics
(n) Chaos in electronic systems
(o) Fractional-order systems

I wish to acknowledge the work of the Co-Editors of the NODYCON 2019 Proceedings: Prof. Balakumar Balachandran (University of Maryland, College Park, MD, USA), Prof. Jun Ma (Lanzhou University of Technology, China), Prof. J. A. Tenreiro Machado (Instituto Superior de Engenharia do Porto, Portugal), Prof. Gabor Stepan (Budapest University of Technology and Economics, Hungary).

The success of NODYCON 2019 relied primarily on the efforts, talent, energy, and enthusiasm of researchers in the field of nonlinear dynamics who wrote and submitted these papers. Special praise is also deserved for the reviewers who invested significant time in reading, examining, and assessing multiple papers, thus ensuring a high standard of quality for this conference proceedings.

Rome, Italy
August 2019

Walter Lacarbonara

Preface for Volume 1: Nonlinear Dynamics of Structures, Systems, and Devices

Volume 1 of the NODYCON Proceedings is composed of 55 papers, which are spread across the following groupings: (a) methods for nonlinear dynamics (8 papers), (b) bifurcations and nonsmooth systems (8 papers), (c) nonlinear phenomena in mechanical systems and structures (12 papers), (d) experimental dynamics, system identification, and monitoring (8 papers), (e) fluid–structure interaction and multibody system dynamics (9 papers), and (f) turning processes, rotating systems, and systems with time delays (10 papers). It is acknowledged that a paper placed in one grouping could have easily been placed in another grouping as well. As one reads through these 55 contributions, one will note the use of a wide range of experimental, analytical, and numerical techniques for study of the nonlinear dynamics of a wealth of systems across different length and time scales.

In the work of N. Potosakis, E. Paraskevopoulos, and S. Natsiavas, an augmented Lagrangian formulation is used to construct models of nonlinear mechanical systems such as vehicle systems subjected to bilateral scleronomic motion constraints. A. O. Belyakov and A. P. Seyranian study domains of stability for parametrically excited systems by using high-order approximations of the monodromy matrix. A. Liu and D. Wagg examine normal form analysis for a two-degree-of-freedom system. E. Kremer investigates system vibratory responses to amplitude-modulated and phase-modulated excitations. A. M. Bersani, A. Borri, A. Milanesi, G. Tomassetti, and P. Vellucci summarize some recent results obtained from studies of the asymptotic properties of important enzyme reactions. Z. Wang, Z. Tang, J. H. Park, and Y. Wang study system modeling for the Hammerstein nonlinear model with unknown but bounded noise. For strongly nonlinear systems, H.-E. Du, G.-K. Er, and V. P. Iu consider construction of frequency-response curves and determination of unstable response regions. Soliton solutions of the Korteweg-de Vries equation are investigated by S. Carillo, M. L. Schiavo, and C. Schiebold.

Two types of bifurcations related to limit directions of nonsmooth vector fields are examined by M. Anatali and G. Stepan. S. Natsiavas and E. Paraskevopoulos study dynamics of multibody systems experiencing impacts with friction. H. Xu and J. Ji use state feedback control to create Neimark–Sacker bifurcation in a vibro-impact system. H. Z. Horvath and D. Takacs consider the stability of suitcases and trailers that are subjected to non-holonomic constraints. I. D. Atanasovska, K. R. Hedrih, and D. B. Momcilovic study the vibro-impact dynamics of spur gears with wear. M. Ramírez, J. Collado, and F. Dohnal provide an efficient means for computing the stability transition curves of coupled Mathieu equations. M. Yadav, S. S. Chaurasia, and S. Sinha study the symmetry in a group of Stuart–Landau oscillators; in particular, with regard to oscillation death states. Dynamics and bifurcations of solutions of the so-called Sprott A system are studied by M. Messias and A. C. Reinol.

J. Awrejcewicz, R. Starosta, and G. Sypniewska-Kamińska examine the dynamics of a three-degree-of-freedom pendulum-spring-damper system in the presence of an external resonance and a two-to-one internal resonance. In the presence of internal resonances, the influence of initial geometric imperfections on the dynamics of a slender cylindrical panel nonlinear response is investigated by F. M. A. Silva, W. A. Vaz, and P. B. Gonçalves. M. Farid and O. V. Gendelman treat sloshing dynamics in partially filled storage tanks. Free oscillations of arbitrarily sagged and inclined cables oscillating around a catenary static profile are studied by A. Mansour, G. Rega, and O. B. Mekki. Nonlinear interactions between flexural and sway oscillations of a laterally braced column are examined by D. Orlando, J. M. P. Raimundo, and P. B. Gonçalves. The influence of temperature on cable dynamics under different excitations is considered by Y. Zhao, H. Lin, L. Chen, and Z. Guo. Behavior of a harmonically forced nonlinear system with a shape memory alloy-based spring is investigated by S. Ramnarace and J. Bridge. Static behavior and free oscillations of shallow circular arches are treated by U. Eroglu and G. Ruta. G. Liu and W. Zhang investigate the response of a composite cantilever plate placed in a subsonic air flow and study the frequency response of this system. A hysteresis damper is examined by D. Li and H. Fang. Nonlinear oscillations of an axially excited beam embedded in a viscoelastic medium are treated by E. Babilio. Energy localization in a chain of coupled, nonlinear oscillators is investigated by A. Kovaleva.

N. Barbieri, M. J. Mannala, R. Barbieri, and G. Barbieri use experimental data based on torsional response to tune nonlinear models of transmission line cables. Nonlinear, stochastic dynamics of a Duffing oscillator are studied by L. G. G. Villani, S. Silva, and A. Cunha, Jr. Hysteretic behavior of wire rope isolators is considered by N. Vaiana, F. Marmo, S. Sessa, and L. Rosati. Nonlinear behavior of rubber shear springs is experimentally examined by S. Gong, S. Oberst, and X. Wang. Experimental studies on the responses of a six-degree-of-freedom parallel manipulator are reported by K. Ringgaard and O. Balling. N. Cavalagli, M. Ciano, G. Fagotti, M. Gioffrè, V. Gusella, and C. Pepi discuss experimental investigations into the dynamic response of a two-storey masonry structure mounted on a shaker table and subjected to a transient excitation with a strong vertical component. Rate dependence of a hysteretic device is experimentally investigated and characterized by M. Antonelli, B. Carboni, W. Lacarbonara, D. Bernardini, and T. Kalmár-Nagy. K. R. Hedrih, S. V. Brčić, and S. Paunović discuss the use of photoelasticity for nonlinear dynamic studies for different applications, including dams.

A combined analytical, experimental, and numerical investigation is used to explore the dynamics of an acoustically levitated sphere by A. Dolev and I. Bucher. Vortex-induced vibrations are studied by V. Kurushina, E. Pavlovskaia, A. Postnikov, G. R. Franzini, and M. Wiercigroch. C. Mannini studies vortex-induced vibrations and galloping dynamics of a cylinder with a rectangular cross section. Dynamics of an aeroelastic system is investigated by C. Demartino, G. Matteoni, and C. T. Georgakis. Computational dynamics of a multibody system in a vertical fluid flow is the subject of the work of Z. Terze, V. Pandža, and D. Zlatar. M. Eugeni, F. Mastroddi, and F. Saltari examine damping models used in flutter analysis of highly flexible aircraft. P. Rosatelli, W. Lacarbonara, A. Arena, and D. J. Inman examine morphing wing dynamics by using computational means. Multibody dynamic studies are carried out by P. Masarati, A. Zanoni, V. Muscarello, R. Paolini, and G. Quaranta to understand how the interactions between the vehicle dynamics and human biomechanics affect helicopter's handling qualities. The use of absolute nodal coordinate formulation for studies of thin plate dynamics is examined by K.-W. Kim, J.-W. Lee, J.-S. Jang, J.-H. Kang, and W.-S. Yoo.

Chatter in turning process is the subject matter of the work presented by B. Beri and G. Stepan. Aperiodic dynamics of spinning shafts with varying rotation speeds are studied by F. Georgiades. M. A. AL-Shudeifat and C. Nataraj study backward whirling of a rotor with fatigue cracks. Inner race defects in rolling element bearings are treated by T. H. Mohamad, S. Ilbeigi, and C. Nataraj. Turning process dynamics are studied by A. Gouskov, G. Panovko, and D. D. Tung. A. Wang, W. Jin, and Q. Lin investigate regenerative effects and friction force effects on chatter during turning operations. Y. Jin and P. Xu study noise-induced transitions in a triple well potential system with a time delay. Dimension reduction for rotor dynamic studies is the topic of the work of K. Lu, H. Zhang, H. Zhou, Y. Jin, Y. Yang, and C. Fu. Drum-type washing machines are studied by C. Baykal, E. Cigeroglu, and Y. Yazicioglu. Wear effects in hydrodynamic bearings used in rotating systems are examined by T. J. Machado and G. C. Stroti.

In conclusion, this volume represents a multifaceted cross section of recent advances in computational methods for nonlinear dynamics, bifurcations, nonlinear phenomena in mechanical systems and structures, experimental dynamics, nonlinear system identification, fluid–structure interaction and multibody system dynamics, turning processes, rotating systems, and nonsmooth system dynamics including systems with time delays. We hope that readers will benefit from the rich work portrayed here on nonlinear dynamics of structures, systems, and devices and that new ideas and future contributions will be inspired.

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College Park, MD, USA	Balakumar Balachandran
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August 2019	

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Part I
Methods for Nonlinear Dynamics

Nonlinear Dynamics of Multibody Systems Using an Augmented Lagrangian Formulation

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Abstract A class of multibody systems subject to bilateral scleronomic motion constraints is investigated. The formulation is based on a new set of equations of motion, expressed as a coupled system of strongly nonlinear second-order ordinary differential equations. After putting these equations in a weak form, the position, velocity, and momentum type quantities are assumed to be independent, leading to a three-field set of equations of motion. Next, an equivalent augmented Lagrangian formulation is set up by introducing a set of penalty terms. This final set of equations is then used as a basis for developing a new time integration scheme, which is applied to several example systems. In those examples, special emphasis is put on illustrating the advantages of the new method when applied to mechanical systems, involving redundant constraints or singular configurations.

Keywords Analytical mechanics · Multibody dynamics · Bilateral motion constraints · Weak form of equations of motion · Augmented Lagrangian

1 Introduction

Research on multibody dynamics helps in developing more efficient and robust numerical techniques for solving challenging engineering problems. This in turn yields useful design gains in many areas, including mechanisms, robotics, biomechanics, automotive, railway, and aerospace structures [1–4]. Typically, the equations of motion for this class of systems are derived and cast in the form of a set of differential-algebraic equations (DAEs) of high index. Earlier attempts to solve these equations are based on index reduction or coordinate partitioning techniques [3, 4]. In contrast, the main objective of this chapter is to first create and employ

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W. Lacarbonara et al. (eds.), *Nonlinear Dynamics of Structures, Systems and Devices*, https://doi.org/10.1007/978-3-030-34713-0_1

a better theoretical foundation and then proceed to development of more advanced numerical schemes.

In the new approach, the equations of motion employed are second-order ordinary differential equations (ODEs). This is achieved by combining concepts of Analytical Dynamics and differential geometry and leads to a natural elimination of singularities associated with DAE formulations from the onset [5]. Since the ulterior motive is the development of an efficient numerical integration scheme, these equations are first put in a convenient weak form. Moreover, the position, velocity, and momentum type quantities are assumed to be independent, forming a three-field set of equations [6]. Finally, the set of equations obtained is solved by application of an augmented Lagrangian formulation, which is set up after introducing appropriate penalty terms [7]. Next, the validity and efficiency of this scheme is tested and illustrated by applying it to a number of characteristic example mechanical systems.

The set of equations of motion employed is included in Sect. 2. Originally, they appear in a strong form and are subsequently put in a three-field weak form. After introducing penalty terms, they are cast eventually in an augmented Lagrangian form. Then, a temporal discretization scheme is developed and numerical results are presented for two mechanical examples in Sect. 3.

2 Equations of Motion: Augmented Lagrangian Formulation

This chapter employs a new set of equations of motion, obtained for a class of multibody mechanical systems subject to equality constraints. The motion is described by a finite number of generalized coordinates $q = (q^1 \dots q^n)$, at any time t [1, 2]. In this way, it can be represented by the motion of a fictitious point, say p, along a curve on the n-dimensional configuration manifold M of the system. Moreover, the tangent vector $\underline{v}$ to this curve belongs to an n-dimensional vector space T_pM, the tangent space of manifold M at p [2]. The systems examined are subject to a set of k motion constraints. For simplicity, these constraints are assumed to be scleronomic, with form

$$\dot{\psi}^R \equiv a_i^R(q)\dot{q}^i = 0. \tag{1}$$

When a constraint is holonomic, its equation can be integrated in the algebraic form

$$\phi^R(q) = 0. \tag{2}$$

The equations of motion of the class of systems examined can be cast in the form

$$\underset{\sim}{h}^* \equiv \underset{\sim}{h}^*_M - \underset{\sim}{h}^*_C = \underset{\sim}{0} \tag{3}$$

on manifold M, where

$$\underset{\sim}{h}^*_M = h_i \, \underset{\sim}{e}^i \quad \text{with} \quad h_i = \left(g_{ij} v^j\right)^{\boldsymbol{\cdot}} - \Lambda^m_{\ell i} g_{mj} v^j v^\ell - f_i \tag{4}$$

and

$$\underset{\sim}{h}^*_C = \sum\nolimits_{R=1}^{k} h_R a_i^R \underset{\sim}{e}^i \quad \text{with} \quad h_R = \left(\overline{m}_{\mathrm{RR}} \dot{\lambda}^R\right)^{\boldsymbol{\cdot}} + \overline{c}_{\mathrm{RR}} \dot{\lambda}^R + \overline{k}_{\mathrm{RR}} \lambda^R - \overline{f}_R. \tag{5}$$

In Eq. (5), the summation convention on repeated indices does not apply to index R. Moreover, the coefficients $\overline{m}_{\mathrm{RR}}$, $\overline{c}_{\mathrm{RR}}$, $\overline{k}_{\mathrm{RR}}$, and $\overline{f}_R$ are determined by the constraints [5]. Equation (3) represents a set of n second-order coupled strongly nonlinear ODEs in the $n + k$ unknowns q^i and λ^R. A complete mathematical formulation is obtained by incorporating the k equations of the constraints, which are expressed originally by Eqs. (1) and (2). In particular, these equations are replaced eventually by

$$g_R = \left(\overline{m}_{\mathrm{RR}} \dot{\phi}^R\right)^{\boldsymbol{\cdot}} + \overline{c}_{\mathrm{RR}} \dot{\phi}^R + \overline{k}_{\mathrm{RR}} \phi^R = 0 \quad \text{and} \quad g_R = \left(\overline{m}_{\mathrm{RR}} \dot{\psi}^R\right)^{\boldsymbol{\cdot}} + \overline{c}_{\mathrm{RR}} \dot{\psi}^R = 0, \tag{6}$$

respectively, for $R = 1, \ldots, k$ [5].

Taking into account Eq. (3) leads first to

$$\int_{t_1}^{t_2} \left(\underset{\sim}{h}^*_M - \underset{\sim}{h}^*_C\right) \left(\underline{w}\right) \mathrm{d}t = 0, \quad \forall \underline{w} \in T_p M, \tag{7}$$

along a natural trajectory on the manifold and within any time interval $[t_1, t_2]$. Moreover, as variation of a function f is defined the derivative of f along vector $\underline{w}$, by

$$\delta f \equiv \underline{w}(f) = f_i w^i. \tag{8}$$

Then, $w^i = \delta q^i$ for each holonomic coordinate, while a little more involved relation is obtained in case of nonholonomic coordinates [6]. In addition, the position, velocity, and momentum variables are considered as independent quantities in the sequel. For this, a new velocity field $\underline{\upsilon}$ is introduced on manifold M, which should eventually be forced to become identical to the true velocity field $\underline{v}$. This means that

$$\upsilon^i = v^i \Rightarrow \delta \upsilon^i = \delta v^i, \tag{9}$$

with variations defined through Eq. (8) by $\delta \upsilon^i = \underline{w}\left(\upsilon^i\right)$ and $\delta v^i = \underline{w}\left(v^i\right)$. In analogy to the action leading to Eq. (7), conditions (9) are imposed by

$$\int_{t_1}^{t_2} \left[\delta\pi_i \left(\upsilon^i - v^i \right) + \pi_i \left(\delta\upsilon^i - \delta v^i \right) \right] \mathrm{d}t = 0, \tag{10}$$

where the quantities $\delta\pi_i$ and π_i are components of co-vectors belonging to the cotangent space $T_p^* M$. In the same spirit, by considering the motion constraints expressed by Eq. (6), the following relation must also be satisfied

$$\int_{t_1}^{t_2} g_R \, \delta\lambda^R \mathrm{d}t = 0, \tag{11}$$

for an arbitrary multiplier $\delta\lambda^R$ and each $R = 1, \ldots, k$. Then, integrating by parts the first term in the integrand for a holonomic constraint yields

$$\left(\overline{m}_{\mathrm{RR}} \dot{\phi}^R \delta\lambda^R \right) \Big|_{t_1}^{t_2} - \int_{t_1}^{t_2} \left[\overline{m}_{\mathrm{RR}} \dot{\phi}^R \left(\delta\lambda^R \right)^{\boldsymbol{\cdot}} - \left(\overline{c}_{\mathrm{RR}} \dot{\phi}^R + \overline{k}_{\mathrm{RR}} \phi^R \right) \delta\lambda^R \right] \mathrm{d}t = 0, \tag{12}$$

while a similar result is also obtained for a nonholonomic constraint.

Next, a similar action is also taken for the velocity components $\dot{\lambda}^R$, by introducing a new vector field on $T_{p_R} M_R$ for each constraint manifold M_R, with components μ^R, together with a new set of Lagrange multipliers σ_R, belonging to the cotangent space $T_{p_R}^* M_R$. As a consequence, the weak formulation is augmented by the terms

$$\int_{t_1}^{t_2} \left[\delta\sigma_R \left(\mu^R - \dot{\lambda}^R \right) + \sigma_R \left(\delta\mu^R - \delta\dot{\lambda}^R \right) \right] \mathrm{d}t = 0, \quad (R = 1, \ldots, k), \tag{13}$$

where $\delta\sigma_R$ represents the component of a co-vector on $T_{p_R}^* M_R$. Then, one can relate the strong time derivatives v^i (of q^i or ϑ^i, for a true or a pseudo-coordinate, respectively) and $\dot{\lambda}^R$ of the position type variables to weak velocities, denoted by υ^i and μ^R, through two new sets of Lagrange multipliers, denoted by $\delta\pi_i$ and $\delta\sigma_R$, respectively.

Finally, appending the terms in Eqs. (10)–(13) to Eq. (7) and performing lengthy manipulations leads eventually to an involved three-field set of equations [6]. Then, since the variations w^i, $\delta\lambda^R$, $\delta\upsilon^i$, $\delta\mu^R$, $\delta\pi_{i,}$ and $\delta\sigma_R$ are independent, collecting the terms in these equations multiplied by these quantities leads to a coupled set of nonlinear algebraic equations. In fact, by adding suitable penalty terms due to the constraints, it is found that the form of these equations remains unaffected, making the substitution

$$\overline{\mu}^R = \mu^R - \xi_R \dot{\phi}^R \quad \text{and} \quad \overline{\lambda}^R = \lambda^R - \xi_R \phi^R, \tag{14}$$

when μ^R and λ^R is multiplied by $\overline{m}_{\mathrm{RR}}$ or $\overline{c}_{\mathrm{RR}}$ and $\overline{k}_{\mathrm{RR}}$, respectively. This provides a convenient and strong basis for developing an appropriate temporal discretization of the equations of motion. For the purposes of the present chapter, this task was