

# **History of Mechanism and Machine Science**

Volume 25

*Series editor*

Marco Ceccarelli, Cassino, Italy

For further volumes:  
<http://www.springer.com/series/7481>

## **Aims and Scope of the Series**

This book series aims to establish a well defined forum for Monographs and Proceedings on the History of Mechanism and Machine Science (MMS). The series publishes works that give an overview of the historical developments, from the earliest times up to and including the recent past, of MMS in all its technical aspects.

This technical approach is an essential characteristic of the series. By discussing technical details and formulations and even reformulating those in terms of modern formalisms the possibility is created not only to track the historical technical developments but also to use past experiences in technical teaching and research today. In order to do so, the emphasis must be on technical aspects rather than a purely historical focus, although the latter has its place too.

Furthermore, the series will consider the republication of out-of-print older works with English translation and comments.

The book series is intended to collect technical views on historical developments of the broad field of MMS in a unique frame that can be seen in its totality as an Encyclopaedia of the History of MMS but with the additional purpose of archiving and teaching the History of MMS. Therefore the book series is intended not only for researchers of the History of Engineering but also for professionals and students who are interested in obtaining a clear perspective of the past for their future technical works. The books will be written in general by engineers but not only for engineers.

Prospective authors and editors can contact the series editor, Professor M. Ceccarelli, about future publications within the series at:

LARM: Laboratory of Robotics and Mechatronics  
DiMSAT—University of Cassino  
Via Di Biasio 43, 03043 Cassino (Fr)  
Italy  
email: [ceccarelli@unicas.it](mailto:ceccarelli@unicas.it)

Danilo Capecchi

# The Problem of the Motion of Bodies

A Historical View of the Development  
of Classical Mechanics

Danilo Capecchi  
Facoltà di Architettura, Dipartimento di  
Ingegneria Strutturale e Geotecnica  
Università di Roma La Sapienza  
Rome  
Italy

ISSN 1875-3442                      ISSN 1875-3426 (electronic)  
ISBN 978-3-319-04839-0            ISBN 978-3-319-04840-6 (eBook)  
DOI 10.1007/978-3-319-04840-6  
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014941511

© Springer International Publishing Switzerland 2014

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law. The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media ([www.springer.com](http://www.springer.com))

# Preface

It is clear that describing the problem of motion of bodies means somehow writing the history of the whole mechanics. My idea is not however to remake a traditional history, although this would be a useful undertaking, as current histories of mechanics are based on historiographical standards that are no longer acceptable. But this would be too hard a task and not feasible for one person alone. My idea is rather to try to fully understand what were the deeper ideas that inspired, first the attempt to understand mechanics, and then to formulate theories that in addition to being explanatory also had predictive value. With this objective in mind, it seemed to me possible to neglect most of the history of fluid mechanics, statics and modern astronomy, while I decided to include part of the history of thermodynamics, which is its own peculiar point of view on motion and is the basis of motion through thermal machines. The subject to be covered still remains too large and it is possible that it would have been more useful to enlist contributions from many scholars, each specialized in a given period. On the other hand, the unitary treatment provided by a single writer would be lost.

Inspired in part by the historical epistemology, I will put aside the various views and theories of a given historical period (synchronic analysis) and then make a comparison between different periods (diachronic analysis). In each period I have chosen one or two meaningful contributions and concentrate on them rather than considering a long inventory of scientist achievements. I think this is the only way to present an intelligible framework of the history of mechanics in a single book.

In order to do that, I consider a number of historical periods, internally quite homogeneous, altogether following a fairly shared use. I consider two periods of antiquity, Classicism-Hellenism (fifth century BC, second century AD) and Middle Ages (1200–1400) in which the authors with documented works are separated by large time intervals. The early Renaissance (1400–1550) follows, from Leonardo to Niccolò Tartaglia with a mildly intense production of texts. There is then Galileo Galilei's and René Descartes's age (1600–1650) with an intense production of texts. The golden age of the second half of 1600 and Isaac Newton's *Philosophiae naturalis principia mathematica* follow. Finally, the mechanics of the eighteenth century, which sees its culmination with Joseph Louis Lagrange's *Mécanique analytique*, is presented and adjustments and refinements of 1800 with the contributions of William Rowan Hamilton and Carl Jacobi. In the latter two phases publications and exchanges of information are very intense.

Within each period there is a certain uniformity of background knowledge, including the type of prevalent mathematics, that define the epistemological conditions. This makes it possible for many scientists to compare their ideas with those of others and criticize them in order to establish a discussion (internal controversy) in some public way, which leads to a clarification and a synthesis of the various positions. The diachronic comparison serves to correlate positions derived from different epistemic conditions and highlight the various incommensurabilities (Kuhn meaning) and the resulting conflicts (external controversy).

As a limit case of the diachronic analysis I will also make a comparison of concepts and problems of selected historical periods with the modern ones. I am indeed convinced that a comparison of the conceptions which we have a good knowledge of and conceptions of the past will highlight the differences, and help to better understand ancient science. In essence, comparison with the modern conceptions, instead of introducing elements of anachronism and finalism, serves precisely for a better contextualization. For example, the comparison between Aristotle's and modern laws of motion—if the positivist intransigent conclusion on the falsity of the former, is avoided—allows us to highlight the differences between our conception of force and that of Aristotle and an incentive to speculate on the reasons for this difference.

Personally, I am convinced of a substantial cumulative growth of science. For I believe that although the problems the scientist are facing vary from period to period and the answers to them depend on the standards of the period, one can identify some problems that have remained unchanged in the core, in the long run, and, over time, have been made precise and provided with more complete responses. Using the historical perspective that focuses on the evolution of the laws of motion, the idea of cumulative development of knowledge and problems appears quite natural. For example, the so-called scientific revolution of the Renaissance, which plausibly seems to have occurred when considered in the broader context of the whole scientific thought, is reduced to a few things, though basic with respect to the evolution of mechanics.

In the cumulative development there are certainly periods of apparent step backwards. Knowledge acquired, perhaps inconspicuously, may disappear into oblivion. It is difficult, however, that there is a total loss; some trace always remains somewhere to offer a new starting point. Hellenistic mathematics, for example, had long been forgotten in the West. However, of it did remain at least the myth, and some manuscripts deposited somewhere; it was a sleeping knowledge, a well-known phenomenon by historians of ideas. When Hellenistic mathematics was recovered it was embedded into a new reality and produced fruit that had not been able to produce at its time. Referring to smaller time intervals, limited to a few centuries, consider for example the discovery of the correct law of the inclined plane. This was known in the thirteenth century, or rather it had been stated and supported with good arguments in some scientific communities. But it had not been adequately disseminated, in part because not everyone accepted the arguments of its probation. The knowledge has been so dormant for a long period, confined to texts that although circulating at least in the universities, were not

studied by people who would have been able to appreciate them. The proper law of the inclined plane was found again with completely different criteria in the sixteenth century by Simon Stevin and Galileo Galilei. But in the seventeenth century the formulation of the thirteenth century was recovered, for example in the text of Pierre Herigone and, shortly after, it was invested with new meanings by René Descartes. A similar argument holds for the theorem of mean velocity. It was proved by both Oxford *calculatores* and philosophers from the terminist school of Paris. But the result did not receive adequate attention and, mostly, was not discussed by scientists interested in studying the motion. The result was found again after more than two centuries by Galileo Galilei and others, probably independently.

The historical sources used in my study mainly come from printed works and scientists official correspondence, but relevance has also been given to unpublished works and private correspondence. In some cases, especially for biographical information and socioeconomic framework I referred to the secondary literature. If the objective had been to understand in-depth the ideas and motivation of the individual scientist and the way the scientific knowledge grows, then it is evident that the analysis of unprinted works would have been an overriding need. Both because the scientist does not publish all the results obtained, and, with few exceptions, scientists are reluctant to publicly present those of their ideas which are not sufficiently precise and documented. My objective is instead to make a collective history of science, so the question is different and the knowledge of the relevant information which the scientists may draw in their time is sufficient. This derives from the cultural background, the experiences of everyday life, and published witness of the several scholars who report both theories and experiment. It is clear that the analysis of unpublished works is still important but to a lesser extent. It mainly serves to clarify the background conceptions of the period.

I want to acknowledge my daughter Giulia, Flavia Marcacci and Francesco Dell'Isola for their comments on some parts of my book. But in particular I want to thank Salvatore Esposito for his accurate reading of the whole text, whose comments allowed me to avoid many inconsistencies and to fill some gaps.

## **Editorial Considerations**

Figures related to quotations are nearly all redrawn to allow a better comprehension. They are however as much as possible close to the original ones. Symbols of formulas are always those of the authors, except cases easily identifiable. Translations of texts from French, Latin, German and Italian are as much as possible close to the original texts. For the Latin, Italian of the fifteenth and sixteenth centuries and French of the seventeenth century a critical transcription has been preferred. In the critical Latin transcription some shortenings are resolved, 'v' is modified in 'u' and vice versa where necessary, ij in ii, following the modern rule; moreover, the use of accents is avoided. In the Italian critical

transcription some shortenings are resolved, 'v' is modified in 'u' and vice versa, and a unitary way of writing words is adopted. In the French critical transcription of the seventeenth century (Descartes's in particular), in most cases the modern spelling is adopted, so for instance *mesme* becomes *même*. Books and papers are always reproduced in the original spelling. For the name of the different characters the spelling of their native language is used, except for the ancient Greeks, for which the English spelling is assumed, and some medieval people, for which the Latin spelling is assumed, following the common use. However, in many cases when the spelling is not fixed, a modern form is assumed. For instance, Gian Battista, Giovan Battista, all become Giovanni Battista, Lodovico becomes Ludovico and so on.

Through the text I searched to avoid modern terms and expressions as much as possible while referring to ancient theories. In some cases, however, I transgressed this resolution for the sake of simplicity. This concerns the use for instance of terms like *mass* and *work* even in the period they were not known. From the context it is however clear that they are used with not technical meaning. The same holds good for expressions like *principle of inertia* and *principle of virtual work*, that were established for sure only after the eighteenth century.

Rome, May 2014

Danilo Capecchi



# Contents

<b>1</b>	<b>The Science of Motion <i>Sive</i> Mechanics</b>	1
1.1	Introduction	1
1.2	Appraisal of Mechanics	6
1.3	Mathematics and Physics	7
1.4	Mathematical Physics	9
1.4.1	The Theory of Potential	14
1.4.2	Epistemological Aspects	17
1.5	Instances of Different Mathematical Involvement	20
1.5.1	Elementary Exposition	20
1.5.2	A Little Bit More Refined Exposition	22
1.5.3	An Axiomatic Exposition of Mechanics	24
<b>2</b>	<b>Greek Period and Middle Ages</b>	31
2.1	Achievements and People	31
2.2	The Framework	32
2.2.1	Discovering New Mathematics	37
2.2.2	Greek Background on Conception of Motion	38
2.3	The Science of Weights	46
2.4	Subalternate Sciences	51
2.4.1	Mechanics as a Subalternate Science	54
2.5	The Medieval Theories of Natural and Violent Motions	57
2.5.1	Natural Motion	57
2.5.2	Violent Motion	62
2.6	Impetus Theory	63
2.6.1	Jean Buridan's Basic Assumptions	66
2.6.2	Nicole Oresme's Variants	72
2.6.3	Albertus de Saxonia and the Spreading of the Theory	78
2.7	Final Remarks	79
<b>3</b>	<b>Humanism and Renaissance</b>	83
3.1	Achievements and People	83
3.2	The Framework	84
3.2.1	The Role of Technicians	87
3.2.2	New Physics and New Mathematics	88

3.3	Mathematics and Physics . . . . .	89
3.3.1	The Debate About the Status of the Subalternate Sciences. . . . .	91
3.4	Ballistics: The Birth of a New Science. . . . .	96
3.4.1	Nova Scientia. . . . .	97
3.5	Conceptions of Motion Compared . . . . .	112
3.5.1	Leonardo da Vinci's Studies on Trajectories . . . . .	112
3.5.2	Tartaglia's <i>Quesiti et Inventioni Diverse</i> . . . . .	116
3.5.3	Girolamo Cardano's Ballistics . . . . .	118
3.5.4	Giovanni Benedetti and the Fall of Bodies. . . . .	120
3.6	Motion of Bodies on the Earth Surface and in the Heaven . . . . .	124
3.6.1	The Motion and the Equilibrium of Bodies . . . . .	124
3.6.2	The Copernican Astronomy . . . . .	125
3.7	Final Remarks. . . . .	127
<b>4</b>	<b>Early Modern Studies on Motion . . . . .</b>	<b>131</b>
4.1	Achievements and People. . . . .	131
4.2	The Framework. . . . .	133
4.2.1	The Role of Subalternate Sciences or Mixed Mathematics. . . . .	135
4.2.2	The New Kepler's Astronomy . . . . .	138
4.3	Galileo's Main Achievements in the Science of Motion. . . . .	147
4.3.1	A Principle of Inertia. . . . .	148
4.3.2	The Composition of Motions . . . . .	152
4.3.3	Relativity of Motions. . . . .	158
4.3.4	The Law of Falling Bodies. . . . .	159
4.3.5	The Pisan Period. . . . .	163
4.3.6	Galileo's Archimedean Mixed Mathematics . . . . .	171
4.4	Evangelista Torricelli's Law of Fall. . . . .	174
4.5	Giovanni Battista Baliani Against Galileo. . . . .	177
4.5.1	De motu naturali gravium solidorum et liquidorum. . . . .	178
4.5.2	Epistemological Position . . . . .	179
4.5.3	Concepts and Empirical Principles . . . . .	184
4.5.4	Propositions . . . . .	188
4.6	Descartes and the Mechanism . . . . .	196
4.6.1	The Philosophy of Nature . . . . .	197
4.6.2	The Center of Agitations . . . . .	202
4.7	Final Remarks. . . . .	215
4.7.1	The Second Galileo Affair . . . . .	216
4.7.2	Fabri's Concept of Impetus and His Law of Natural Numbers. . . . .	217
4.7.3	The Defense Organized by Mersenne . . . . .	219

<b>5</b>	<b>The Golden Age</b> . . . . .	223
5.1	Achievements and People . . . . .	223
5.2	The Framework . . . . .	225
5.2.1	The New Mathematics of Infinitesimal . . . . .	226
5.3	The Causes of Motion: Forces, Work, Energy . . . . .	228
5.3.1	Force as Force . . . . .	228
5.3.2	Force as Work . . . . .	229
5.3.3	Force as Kinetic Energy . . . . .	229
5.4	The Impact of Bodies . . . . .	230
5.5	The First General Explanations of Motion . . . . .	235
5.5.1	John Wallis' Impressed Force . . . . .	235
5.5.2	Christiaan Huygens' Centrifugal Force . . . . .	240
5.6	The Dynamics of Isaac Newton . . . . .	243
5.6.1	The Concept of Force in Newton's Principia . . . . .	243
5.6.2	Moving Toward the Principia . . . . .	252
5.6.3	The Laws of Motion . . . . .	255
5.6.4	Evolution of the Second Law . . . . .	260
5.6.5	The Concept of Mass . . . . .	262
5.6.6	The Dynamics of the Principia . . . . .	264
5.6.7	Applications of the Second Law . . . . .	269
5.6.8	The Logical Status of Newton's Mechanics . . . . .	276
5.7	The Dynamics of Gottfried Wilhelm Leibniz . . . . .	279
5.7.1	The Force in Leibniz's Metaphysics . . . . .	280
5.7.2	Force and Motion . . . . .	283
5.7.3	Living and Dead Forces . . . . .	284
5.7.4	Mature Works . . . . .	286
5.8	Final Remarks . . . . .	299
<b>6</b>	<b>The Motion of Solid Bodies</b> . . . . .	303
6.1	Achievements and People . . . . .	303
6.2	The Framework . . . . .	305
6.2.1	Establishment of the Infinitesimal Calculus and Decline of Geometry . . . . .	307
6.2.2	Newtonianism in Europe . . . . .	310
6.2.3	The Search for New Principles . . . . .	313
6.3	Living Force Conservation . . . . .	315
6.3.1	The True Measure of Force and the Vis Viva Controversy . . . . .	315
6.3.2	The Principle of Living Forces . . . . .	318
6.4	Vector and Analytical Mechanics . . . . .	327
6.4.1	Vector Mechanics . . . . .	327
6.4.2	Analytical Mechanics . . . . .	338
6.5	The Epistemology of Mechanics . . . . .	348
6.5.1	The Ontology of Force . . . . .	351

- 6.6 A New Concept of Machine . . . . . 355
  - 6.6.1 The Science of Geometric Motions or Kinematics . . . . . 357
  - 6.6.2 Conservation of Work . . . . . 361
- 6.7 Final Remarks. . . . . 363
- 7 Inanimate Bodies Start Moving by Themselves . . . . . 365**
  - 7.1 Achievements and People . . . . . 365
  - 7.2 The Framework. . . . . 367
    - 7.2.1 The Naturphilosophie . . . . . 369
  - 7.3 Perfecting the Theoretical Aspects. . . . . 371
    - 7.3.1 The Study of Relative Motions. . . . . 371
    - 7.3.2 The Mechanics of William Rowan Hamilton . . . . . 376
  - 7.4 Opening of New Perspectives . . . . . 386
    - 7.4.1 Mechanics of Machines . . . . . 387
    - 7.4.2 Mechanics of Structures. . . . . 400
  - 7.5 Hydraulic Machines . . . . . 414
    - 7.5.1 Old Hydraulic Machines . . . . . 415
    - 7.5.2 New Hydraulic Machines. . . . . 428
  - 7.6 The Emergence of Thermodynamics . . . . . 430
    - 7.6.1 Conservation of Energy . . . . . 430
    - 7.6.2 Thermal Machines. . . . . 440
    - 7.6.3 The Energetism. . . . . 447
  - 7.7 Final Remarks. . . . . 454
    - 7.7.1 Internal Controversies . . . . . 455
    - 7.7.2 External Controversies. . . . . 455
- Appendix A: Quotations . . . . . 459**
- References . . . . . 525**
- Author Index . . . . . 549**