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Kinetic energy storage

Theory and practice of advanced flywheel systems

G. Genta

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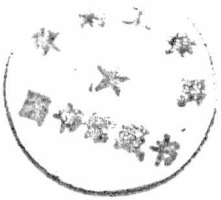

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First published 1985

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British Library Cataloguing in Publication Data
Genta, G.
Kinetic energy storage: theory and practice of advanced flywheel systems.
1. Energy storage 2. Fly-wheels
I. Title
620.1'054 TJ165

ISBN 0-408-01396-6

Photoset by Mid-County Press, London SW15
Printed in Great Britain at the University Press, Cambridge

Kinetic energy storage

Theory and practice of advanced flywheel systems

To Franca and Alessandro

'From this follows that if the (Supreme) Intelligence refrained from moving the heavens they would continue to move, that is, to rotate, for some time thanks to the very virtue that sustains and continues circular motion, as it does in the case of the potter's wheel, which continues to spin for some time after its prime mover has ceased to move it'.

Francisci de Marchia, 'In libro sententiarum', 1323

'And there is an experiment: if you spin fast a large and heavy grinding wheel of a blacksmith and then you refrain from moving it, it continues to move owing to the impetus it acquired; moreover you could not stop it in a short time, but that impetus would be slowly and continuously dissipated owing to the resistance due to the gravity of the wheel until the motion stops; and perhaps if the wheel would last forever without any reduction or alteration and if there were no resistance to corrupt that impetus, the wheel would be moved for ever by it'.

Johannis Buridani, 'Quaestiones super libris quattuor de caelo et mundo', c. 1340

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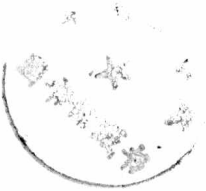
Preface



Flywheels are among the most ancient mechanical devices known to man, and the use of the wheel for storing energy seems to be older than its use as a means of supporting vehicles.

It was, however, only since the early 1970s that the awareness of the growing costs of energy and of an eventual shortage of fossil fuel supplies engendered an interest in energy conservation and, in consequence, in energy storage devices, among which are flywheels.

Research on 'advanced' flywheels which can store as much energy per unit mass as other types of energy storage device has been undertaken in many countries, often supported by public funds.

This book is an attempt to systematize the results of research and to present and up-to-date 'state of the art' review of the subject, which the author feels is justified for the following reasons.

Firstly, there is no agreement on the practicability and the future possibilities of flywheel energy storage from either the technical or the economic viewpoint. Over-optimistic statements found in scientific literature often vie with unjustifiably pessimistic views. There is therefore a need to present unbiased information to help the designer or manager to appraise these devices in an informed and systematic way, though the author is bound to admit that his own moderate optimism on the future of flywheel devices may at times colour these pages. The reader cannot fairly expect otherwise.

Secondly, flywheel technology is a complex subject and, as far as high energy density flywheels are concerned, a highly specialized one, and it is not unusual to hear false statements or incorrect interpretations of recent results from otherwise well-informed persons. Nor should it be forgotten that flywheels are, and have been for centuries, a fundamental element of many machines. Their design is often regarded only in their ability to supply the required inertia to a rotating part without much concern for other characteristics.

Some of the results of the work aimed to produce viable flywheel accumulators can also be used to refine the design of flywheels used in 'conventional' applications, and so upgrade their performances.

The aims of this book are consequently twofold:

(i) to assemble information from various sources for those who have to decide the pros and cons of the various types of kinetic energy accumulator for given applications, and for the designers who must implement that decision.
(ii) to reveal to designers of rotating machinery of all types the full potential of modern flywheel technology.

Flywheel technology involves many aspects which belong traditionally to other disciplines. Thus the author's own technical background might be excused for any emphasis on the design of the rotor and its dynamic behaviour, while other perhaps not less-important elements receive less attention, consistent also with the need for reasonable economic constraints on the length of this book. An extended bibliography is intended for those who wish to delve deeper into these aspects.

The author expresses his sincere thanks to all persons and institutions without whose co-operation these pages would not have been written, and particularly to his colleagues and technicians of the Dipartimento di Meccanica of Politecnico (Technical University) di Torino, who took part in the research work on flywheel technology and whose suggestions, criticism and general exchange of ideas contributed much to this work; also to the Italian National Research Council (C.N.R.) who sponsored the work and under whose founding the research is proceeding and whose contribution is much appreciated. Thanks are also due to those who have participated in the research, and their research managers, in particular Dr P. Motta of CISE (formerly with Industrie Pirelli S.p.A.) whose co-operation was essential for the experimental part of the work, and to other research institutions with which a constant exchange of opinions and results has proven invaluable, especially to Dr D. W. Rabenhorst, whose fruitful and objective work at the Applied Physics Laboratory, Johns Hopkins University, has proved to be an invaluable source of ideas and encouragement.

The author also wishes to register his appreciation of the help given by Dr T. M. Barlow of Lawrence Livermore National Laboratory, who is responsible for the Mechanical Energy Storage Technology Project, sponsored by the US Department of Energy, and who provided the author with all the printed matter issued on the subject.

Last, but not least, a sincere thanks to my wife, Franca, both for her encouragement and for having done the tedious work of revising the manuscript.

G. Genta

Symbols

a	acceleration; effective molecular diameter
c	radial clearance between the flywheel and the housing; damping coefficient
d	distance
d_m	average diameter of a bearing
d_s	diameter of a shaft
e	energy; base of natural logarithms
f_0	rolling resistance coefficient (at zero speed)
g	acceleration of gravity
h	disc thickness at radius r
i	imaginary unit ($i=\sqrt{-1}$)
k	ratio between the specific heat at constant pressure and the specific heat at constant volume; stiffness
m	mass; mass of the molecules
m_a	'apparent' mass of the vehicle
m_m	molecular mass
p	pressure
q_i	generalized coordinate
r	radius
r_i	inner radius
r_j	radius of inertia
r_o	outer radius
t	time
u	radial displacement; eccentricity
$\bar{v}$	mean velocity of the molecules
$\bar{z}$	complex coordinate
B	parameter for constant stress discs and bars; ratio $\sigma_{u_L}/\sigma_{u_T}$
C_m	aerodynamic drag torque coefficient
C_x	aerodynamic X-force coefficient
E	Young's modulus
G	shear modulus
$\bar{H}$	angular momentum

I	area moment of inertia
J	mass moment of inertia
K	shape factor; term expressing the dependence of the rolling resistance from the speed; Boltzmann constant
K_n	Knudsen number
M	moment; Mach number
M_a	aerodynamic drag torque
N	number of spokes
N_A	Avogadro's number
P	power
Q_i	generalized force
Q_{ij}	element of the plane stress stiffness matrix
R	universal gas constant
R_{c_i}	inner radius of the containment ring
R_e	Reynolds number
S	area; pumping speed
S_{ij}	element of the elastic compliance matrix
T	(absolute) temperature; period
T_c	Sutherland constant
V	volume; velocity
V_f	fibre content of a composite material (in volume)
V_s	velocity of sound
α	thermal expansion coefficient
β	ratio r_i/r_o
β_{ij}	element of the plane strain compliance matrix
γ	shear strain; ratio $\sqrt{Q_{cr}\|Q_{rr}}$; structural damping factor (loss factor)
δ	ratio α_c/α_r; radial clearance in squeeze film dampers
ε	normal strain; non-dimensional eccentricity
η	efficiency; viscosity
θ	polar angle
λ	mean free path of the molecules; whirl speed
μ	ratio E_c/E_r
ν	Poisson's ratio; kinematic viscosity
ξ	velocity factor
ρ	density of the material
ρ_a	density of air
ρ_g	density of the gas in the flywheel container
σ	normal stress
σ_e	equivalent stress
σ_u	ultimate strength of the material
σ_y	yield stress
τ	shear stress; transmission ratio
$\bar{\varphi}$	complex variable
χ	non-dimensional coordinate
ω	angular velocity (spin speed)
χ	dynamic unbalance
Ω	angular velocity
$(\,)_{,x}$	differentiation with respect to the variable x
X	cross product of vectors

Subscripts

c	circumferential direction
e	equivalent
f	flywheel; fibre
i	inner
m	matrix
o	operating; outer
o, o	operating overall
r	radial direction; containment ring
s	shaft
u	ultimate
u.f.	ultimate flywheel
z	axial direction
L	longitudinal direction of unidirectional composite materials
T	transverse direction of unidirectional composite materials

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