Michel
Remoissenet

WAVES CALLED SOLITONS

Concepts and Experiments

Second Revised and
Enlarged Edition

孤子波

第2版

Springer-Verlag
世界图书出版公司

M. Remoissenet

Waves Called Solitons

Concepts and Experiments

Second Revised and Enlarged Edition
With 135 Figures

Springer-Verlag
世界图书出版公司
北京 · 广州 · 上海 · 西安

Professor Michel Remoissenet

Université de Bourgogne, Laboratoire de Physique
Phénomènes non-linéaires – URA CNRS no 1796
6 Bd Gabriel, F-21000 Dijon, France
E-mail: remsnet@satie.u-bourgogne.fr

Library of Congress Cataloging-in-Publication Data

Remoissenet, M.
Waves called solitons : concepts and experiments / Michel Remoissenet. -- 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 3-540-60502-9 (softcover : alk. paper)
1. Solitons. I. Title.
QC174.26.W28R46 1996
530.1'55353--dc20 95-49021
CIP

ISBN 3-540-60502-9 2nd Edition
Springer-Verlag Berlin Heidelberg New York

ISBN 3-540-57000-4 1st Edition
Springer-Verlag Berlin Heidelberg New York

Cover Design: Struve & Partner, Atelier für Grafik-Design, Heidelberg
Typesetting: Data conversion by Springer-Verlag
SPIN 10516388 55/3144 – 5 4 3 2 1 0 – Printed on acid-free paper

书　　名：Waves Called Solitons　2nd ed.
作　　者：M. Remoissenet
中 译 名：孤子波
出 版 者：世界图书出版公司北京公司
印 刷 者：北京中西印刷厂
发　　行：世界图书出版公司北京公司（北京市朝阳门内大街 137 号　100010）
开　　本：大 32 开　850 × 1168　　印　张：8.75
版　　次：1999 年 4 月第 1 版　　1999 年 4 月第 1 次印刷
书　　号：7-5062-4105-6/ O•245
版权登记：图字 01-98-1785
定　　价：40.00 元

Preface to the Second Edition

Encouraged by the friendly reception given to the first edition, I have preserved its basic form and most of the details. Apart from some corrections, minor changes, and addition of references where it was necessary, I have made the following changes.

Chapter 1 was expanded by a discussion of the discovery of solitons in the field of electromagnetic waves and optics. A new section devoted to nonlinear transmission lines and their applications in the microwave range has been added to Chap. 3. It seems to me that it was important to describe laboratory experiments on modulational instability, and subsequent generation of solitons, both in electrical transmission lines and in deep water in Chaps. 4 and 5. A description of a very simple experimental pocket version of the mechanical transmission line has been included in Chap. 6. Such a versatile and useful device should stimulate a practical approach to soliton physics. Chapter 7 was completed by a short presentation of some recent experimental results on discrete Josephson transmission lines. A discussion of the experimental modulational instability of coupled optical waves and a simple look at quantum solitons were added to Chap. 8 in order to introduce the reader to such remarkable topics.

Of the many people who made valuable comments on the first edition, I am particularly grateful to M. Dragoman, Y.S. Kivshar and A.W. Snyder.

I would like to thank R.S. MacKay whose corrections and suggestions helped refine the manuscript of this second edition.

I also take pleasure in thanking my Dijon colleague J.M. Bilbault and ex-student P. Marquié whose research efforts are responsible for some part of the new material added to this edition. I also wish to extend my appreciation to M. Pauty for a useful comment on the historical background.

Again, for this edition I have benefited from the technical assistance of B. Michaux and D. Arnoult in designing and performing new experiments, and in preparing a number of new diagrams and photographs.

Dijon
November 1995

Michel Remoissenet

Preface to the First Edition

Nonlinearity is a fascinating element of nature whose importance has been appreciated for many years when considering large-amplitude wave motions observed in various fields ranging from fluids and plasmas to solid-state, chemical, biological, and geological systems. Localized large-amplitude waves called *solitons*, which propagate without spreading and have particle-like properties, represent one of the most striking aspects of nonlinear phenomena. Although a wealth of literature on the subject, including theoretical and numerical studies, is available in good recent books and research journals, very little material has found its way into introductory texbooks and curricula. This is perhaps due to a belief that nonlinear physics is difficult and cannot be taught at an introductory level to undergraduate students and practitioners. Consequently, there is considerable interest in developing practical material suitable for students, at the lowest introductory level.

This book is intended to be an elementary introduction to the physics of solitons, for students, physicists, engineers and practitioners. We present the modeling of nonlinear phenomena where soliton-like waves are involved, together with applications to a wide variety of concrete systems and experiments. This book is designed as a book of physical ideas and basic methods and not as an up-to-the-minute book concerned with the latest research results. The background in physics and the amount of mathematical knowledge assumed of the reader is within that usually accumulated by junior or senior students in physics.

Much of the text of this book is an enlargement of a set of notes and descriptions of laboratory experiments developed over a period of years to supplement lectures on various aspects of wave motion. In spite of the diversity of the material, the book is not a collection of disconnected topics, written for specialists. Instead, I have tried to supply the practical and fundamental background in soliton physics, and to plan the book in order that it should be as much as possible *a self-contained and readable interdisciplinary whole*. Often, the important ideas or results are repeated several times, in different contexts. *Many of my choices of emphasis and examples have been made with experimental aspects in mind. Several experiments described in this book can be performed by the reader.* Although numerical studies play an important role in nonlinear science, I will not consider them in this book because they are described in a considerable body of literature.

In order to facilitate the use of this book, many illustrations have been included in the text and the details of theoretical calculations are relegated to appendices at the end of each chapter. A number of basic references are given as well as references intended to document the historical development of the subject. The referencing is not systematic; the bibliography listed at the end of the book serves only to advise the reader which sources could be used to fill in gaps in his or her basic knowledge and where he or she could turn for further reading.

The text is organized as follows. Our introduction in Chap.1 is devoted to the beautiful historical path of the soliton. The fundamental ideas of wave motion are then set forth in Chap.2 using simple electrical transmission lines and electrical networks as examples. At an elementary level, we review and illustrate the main properties of linear nondispersive and dispersive waves propagating in one spatial dimension. In Chap.3, we consider waves in transmission lines with nonlinearity. These simple physical systems are very useful for a pedagogical introduction to the soliton concept, and they are easy to construct and to model, allowing one to become quickly familiar with the essential aspects of solitary waves and solitons, and their properties. Specifically, we first examine the effect of nonlinearity on the shape of a wave propagating along a nonlinear dispersionless transmission line. Then we consider *the remarkable case where dispersion and nonlinearity can balance to produce a pulse-like wave with a permanent profile*. We describe simple experiments on pulse solitons, which illustrate the important features of such remarkable waves. In Chap.4 we consider the *lattice solitons*, which can propagate on an electrical network; then we examine periodic wavetrains, and modulated waves such as *envelope or hole solitons*, which can travel along electrical transmission lines.

Chapter 5 concentrates on such spectacular waves as the hydrodynamic pulse soliton, which was first observed in the nineteenth century, and the hydrodynamic envelope soliton. Simple water-tank experiments are described.

In Chap. 6, by using a chain of coupled pendulums, that is, a mechanical transmission line, we introduce a new class of large amplitude waves, known as *kink solitons* and *breather solitons* which present remarkable particle-like properties. Simple experiments that allow one to study qualitatively the properties of these solitons are presented.

Chapter 7 deals with a more sophisticated device: the superconductive Josephson junction. Here the physical quantity of interest is a quantum of magnetic flux, or *fluxon*, which behaves like a kink soliton and has properties remarkably similar to the mechanical solitons of Chap.5. In Chap.8 *bright and dark solitons* emerge, which correspond to the optical envelope or optical hole solitons, respectively. They can be observed in optical fibers where exploitation of the typical dispersive and nonlinear effects has stimulated theoretical and experimental studies on nonlinear guided waves.

Whereas the previous chapters are concerned with solitons in the macroworld, Chap.9 deals with nonlinear excitations in the microworld. Specifically, we consider the soliton concept in the study of nonlinear atomic lattices. The nonlinear equations that are encountered in the soliton story and models of several systems described in the text can be solved by using remarkable and powerful mathematical techniques, the main steps of which are given in the last chapter.

If a substantial fraction of users of this book feel that it helped them to approach the fascinating world of nonlinear waves or enlarge their outlook, its purpose will have been fulfilled. I hope the reader will feel encouraged to bring to my notice any remaining errors and other suggestions.

I have greatly benefited from frequent discussions with my colleagues and students. I am particularly grateful to Jean Marie Bilbault, who went over the entire manuscript and gave me invaluable comments.

I would also like to thank Alwyn Scott whose criticism and suggestions helped refine the manuscript.

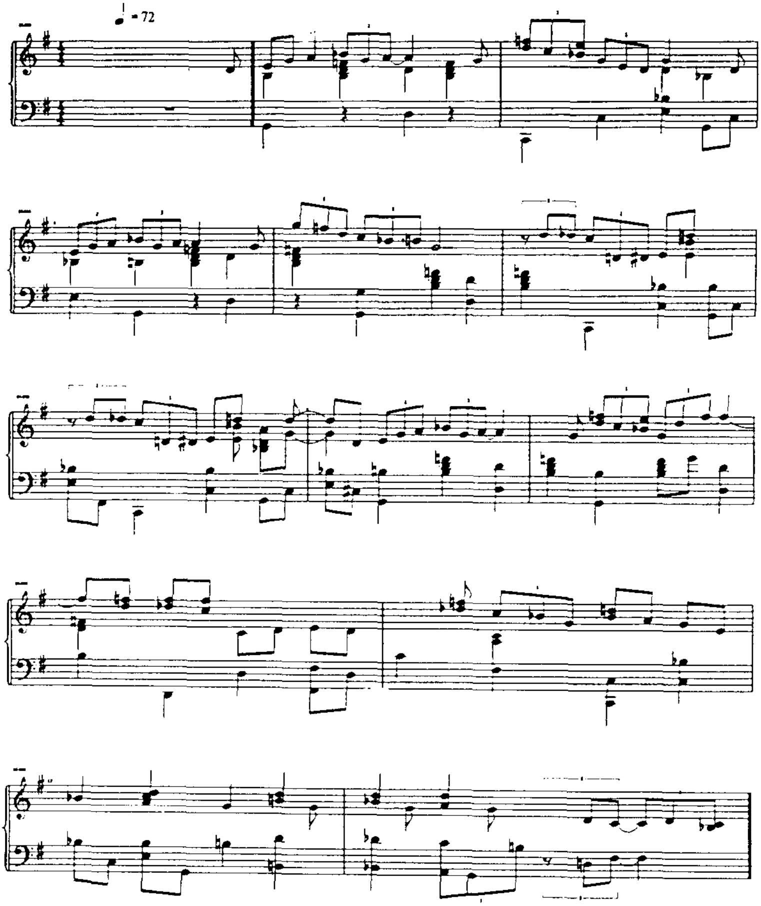
I also wish to extend my appreciation to Patrick Marquié, Guy Millot, Jean François Paquerot, Michel Peyrard, and Claudine and Gérard Pierre for their comments on various chapters. Special thanks go to Bernard Michaux for his assistance in designing and performing experiments, and improving numerous illustrations throughout the book. Finally, it is a pleasure for me to acknowledge the technical assistance I have received from Dominique Arnoult and Claudine Jonon.

Dijon
October 1993

Michel Remoissenet

Solitons Blues

Music: Michel Remoissenet
Arrangement and transcription:
Michel Thibault



This book is dedicated to all the scientists
who have made the soliton concept a reality

On the occasion of a Conference on Nonlinear Coherent Structures in Physics and Biology organized by J. C. Eilbeck and D. B. Duncan, physicists and mathematicians solemnly gathered, on 13 July 1995, by an aqueduct of the Union Canal (see Nature, **376**, 373, 1995). This acqueduct, which was named *Scott Russell aqueduct* after a ceremony carried out by Alwyn Scott, is located at Hermiston near the site of the present Heriott-Watt University (Edinburgh). Martin Kruskal was one of the gathering, attempting, with the help of a borrowed boat to recreate *the solitary wave* of John Scott Russell (see Sect.1.2) which can be observed propagating a few meters in front of the boat. (Photo by K. Paterson, reproduced by kind permission of Heriot-Watt University).

Contents

1 Basic Concepts and the Discovery of Solitons

Today, many scientists see nonlinear science as the most important frontier for the fundamental understanding of Nature. The soliton concept is now firmly established after a gestation period of about one hundred and fifty years. Since then, different kinds of solitons have been observed experimentally in various real systems, and today they have captured the imagination of scientists in most physical discipline. They are widely accepted as a structural basis for viewing and understanding the dynamic behavior of complex nonlinear systems. Before introducing the soliton concept via its remarkable and beautiful historical path we compare briefly the linear and nonlinear behavior of a system.

1.1 A look at linear and nonlinear signatures

First, let us consider at time t the response R_1 of a linear system, an amplifier for example, to an input signal $E_1 = A \sin\omega t$ of angular frequency ω, as sketched in Fig. 1.1. In the low amplitude limit the output signal or the response of the system is linear, in other words it is proportional to the excitation

$$R_1 = a_1 E_1. \tag{1.1}$$

Here a_1 is a quantity that we assume to be constant (time independent) to simplify matters. If we double the amplitude of the input signal, the amplitude of the output signal is doubled and so on. The sum of two input signals E_1 and E_2 yields a response which is the superposition of the two output signals,

$$R = a_1(E_1 + E_2) = R_1 + R_2, \tag{1.2}$$

and a similar result holds for the superposition of several signals.

Next, if the amplitude of the input signal gets very large, distortion occurs as a manifestation of overloading. In this case, the response is no longer proportional to the excitation; one has

$$R = a_1E_1 + a_2E_1^2 + a_3E_1^3 + \ldots = a_1E_1\left(1 + \frac{a_2}{a_1}E_1 + \frac{a_3}{a_1}E_1^2 + \ldots\right) \tag{1.3}$$

and signals at frequencies 2ω, 3ω, and so on, that is, *harmonics of the input signal are generated.* In some cases a chaotic response can occur: this phenomenon will not be considered in this book. Moreover, the sum of two signals at the input results not only in the sum of responses at the output but also in the product of sums and so on. *The superposition of states is no longer valid.*