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BOOK REVIEW

Liquid Sloshing Dynamics: Theory and Applications. By R. A. Ibrahim. Cambridge University Press, 2005. 970 pp. ISBN 0 521 83885 1. £160.

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The subject of sloshing concerns the free-surface wave motion of a liquid inside a container. The container may be at rest or it could be shaken or it may move due to the nett hydrodynamic forces acting on the walls of the container. We all know how badly behaved cups of hot drinks can be when we try carrying two mugs for example through sprung-loaded fire doors, or when we rest a brim-full glass on a thick-piled carpet.

It is the interaction between a liquid and its container which, for me, is the most interesting side of sloshing, and Professor Ibrahim's book brings this out to the full. An important parameter is the fill depth (the ratio of the depth of fluid to its maximum value). In a closed vessel the waves behave quite differently when the tank is nearly full from the sloshing when it is almost empty, as jack-knifed petrol-tanker drivers have discovered. A reasonably safe home experiment is as follows: take a half-full screw-top plastic milk carton and throw it into the air (spinning it as much as you like). Look at how very differently from a rigid body the carton moves.

Sloshing theory has been fed by problems in the bulk transport of oil by ships, in road vehicles and aboard spacecraft. Large-amplitude sloshing can bring about liquid impact with the walls or the roof of a closed tank. The pressures due to direct impact (or secondary splashes) may be high enough to explain the damage or even rupture of tanks. This may lead to further catastrophe if the liquid is dangerously hot, cold, toxic or valuable. On the other hand the theory of sloshing has helped optimize some engineering solutions, such as in the design and tuning of ship anti-rolling devices and, recently, with earthquake-vibration absorbers in new buildings in Japan.

The book has twelve chapters, grouped into four parts. Part I uses the linear theory of water waves alongside an assumption that the forced motion of the tank is small enough in amplitude that free boundary conditions can be posed at fixed locations. This means linear equations can make an adequate model. Part II is longer and treats nonlinear and parametric sloshing. The last of its four chapters considers the impact of the surface of a sloshing wave onto an interior wall of a tank. The high pressures of impact can lead to sudden tank motions or even vessel damage. The effect on the liquid of suddenly accelerating the tank is also treated, but it would have been good to see cited the 1994 *Journal of Fluid Mechanics* paper by A. C. King and D. J. Needham (vol. 268, pp. 89–101) on the asymptotic small-time treatment of this initial wavemaker problem. The numerics of the discretized model equations of liquid impact could have been supplemented by the theory of pressure-impulse. Instead the author's emphasis is on the experimental work which has been published on impact in containers. Part III is the longest section at 210 pages. Here various classes of problem are modelled, such as the elastic response of a container's walls or bed under dynamic fluid loading. Chapter 9 treats the rigid shell (full or partially filled), which is either free to move or which is shaken by a prescribed displacement and frequency. Chapter 10 includes a discussion of technological applications, such as ship anti-rolling devices and earthquake-vibration absorbers for buildings. Two chapters make up the fourth and final part, which should interest designers of liquid-fuelled rockets and spacecraft: Chapter 11 is about rotating fluids and Chapter 12 concerns sloshing in conditions of microgravity. There is one appendix on dimensionless parameters in fluid mechanics, a bibliography of 2600 references and an index. There are no distracting web pages and few footnotes.

It is a lot to ask an author, but software might grant the following wish: the lengthy bibliography could be made to list the pages on which each reference is cited. This would be a nice extra feature for researchers and a supplement to the index. Surprisingly there is no list of notations – this is something which I missed when trying to find definitions of symbols in some of the mathematical expressions.

In my department (UEA, Norwich), each of our Master of Mathematics students writes a substantial final-year project. I wish I had seen a copy of this book before supervising a recent student who investigated sloshing, because there are 2600 references which we could have picked over. Indeed this book grew out of an earlier review which Professor Ibrahim co-authored. Parts of the book read like a review, and the appraisal of others' work is a major and attractive feature of the book. Each chapter ends with a section named 'Closing Remarks' which lists some topics which are not covered, but where supplementary references send on the researcher. This may be enough for a reader seeking new areas worth studying in sloshing. There are fascinating articles on magnetic liquid sloshing, cryogenics and random excitation. But there is little on environmental topics such as earthquake-induced sloshing in reservoirs; I found nothing on wave energy extraction (where sloshing occurs in oscillating water columns under a variable air pressure). Nor could I find anything on harbour and lake seiching, where hazardous long-period wave-sloshing can be induced by winds or tides. Nevertheless I agree with H. N. Abramson, who wrote in the foreword

> *this is a monumental work in that it attempts*
> *to cover almost every aspect of liquid sloshing.*

In such a long book there are bound to be some typographical mistakes, but I grew worried by the high frequency of errors that I noticed. For example the very first citation has the wrong date, by 100 years. In the bibliography, three of the six papers by G. G. Stokes were cited in the wrong century. The very review article which led to this book is R. A. Ibrahim *et al.* (2001): Recent advances in liquid sloshing dynamics, *ASME Appl. Mech. Rev.*, vol. 54(2), pp. 133–199, a reference which is out of order among ten references to "R. I. Ibrahim", of whom I can find no published work on databases. John Scott Russell's marvellous 1844 paper appears as an entry so abbreviated as to be obscure. (Do read J. S. Russell (1844): Report on waves, *Report of the 14th meeting of the British Association for the Advancement of Science*, pp. 311–392 and 11 plates.)

Another kind of error is in Table 1.2, whose source is another author. While checking a numerical oddity, I found five errors in the first fifty numbers tabulated. On page 150 we are told Thomas Graham lived from 1805 until 1969 [sic], a feat even greater than his coining of the word 'colloid'. And so on. Perhaps for a second edition these small but numerous errors could be corrected.

The black-and-white illustrations are nearly all fine figures which define coordinates, or display functional relations or experimental measurements. The captions and legends are not always helpful; reference to the main text must be made to find what is being plotted or which units are being used. There are no photos of sloshing in containers and I found only two figures devoted to the instantaneous streamlines and flow patterns, found in a sloshing simulation. Perhaps I am not a typical reader, but

I think photographs or sketches of real fluid flows stimulate my research. There are few illustrations even of the free-surface motions. I think this anatomy of sloshing could be improved by some colour and some explanatory graphics, to bring alive its inner workings.

At the end of the text there is a list of non-dimensional numbers common in fluid mechanics, but arguably the Euler (cavitation) and Strouhal numbers are absent. Despite the appendix, little use is made of dimensional analysis, either to simplify a class of problems or to persuade us that certain terms in the full governing equations may be left out. For example, there are quantities which the author states are 'small', without reference to any scale of comparison. Another criticism has an example in section 8.2, where in analysing elastic boundaries, quantities are defined as the solutions of boundary-value problems whose solution is not unique. Mine are the criticisms of an applied mathematician, but there is a lot of mathematical modelling in the book which deserves scrutiny. For example an engineer may need to be sure of his or her theoretical ground when modelling a problem connected with safety.

Which brings me to think: Who will find this book interesting enough to pay its full list price? There are no exercises and it is not a textbook, even for students on a postgraduate course. Anyone writing computer code will be disappointed by the summary descriptions of numerical methods and packages (such readers will probably go to the original sources). It is a book which describes mathematical methods, which might be used on problems beyond the examples treated, but such application may demand at least as much skill from the reader as the author has shown. On the positive side, an engineer or fluid dynamicist might profitably use the book to find out what results and measurements are in the literature, and as a source of ideas for approaching calculations for containers which are rectangular, cylindrical, spherical or conical. Chapter 5 is helpful in this respect as it treats pendulum systems which are mechanically equivalent to waves sloshing in moving tanks.

Overall this work has no rivals in book form in English, and will be a useful source of reference for any fluid mechanics library.

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