FLUID MECHANICS AND ITS APPLICATIONS

Peter W. Carpenter and Timothy J. Pedley (Eds.)

IUTAM Symposium on Flow past Highly Compliant Boundaries and in Collapsible Tubes



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Flow past Highly Compliant Boundaries and in Collapsible Tubes

FLUID MECHANICS AND ITS APPLICATIONS Volume 72

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Flow past Highly Compliant Boundaries and in Collapsible Tubes

Proceedings of the IUTAM Symposium held at the University of Warwick, United Kingdom, 26–30 March 2001

Edited by

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PREFACE

The IUTAM Symposium on Flow in Collapsible Tubes and Past Other Highly Compliant Boundaries was held on 26-30 March, 2001, at the University of Warwick. As this was the first scientific meeting of its kind we considered it important to mark the occasion by producing a book. Accordingly, at the end of the Symposium the Scientific Committee met to discuss the most appropriate format for the book. We wished to avoid the format of the conventional conference book consisting of a large number of short articles of varying quality. It was agreed that instead we should produce a limited number of rigorously refereed and edited articles by selected participants who would aim to sum up the state of the art in their particular research area. The outcome is the present book.

Peter W. Carpenter, Warwick Timothy J. Pedley, Cambridge May, 2002.

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ACKNOWLEDGEMENT

We are very grateful to IUTAM and KLUWER for their financial support of this conference. We would also like to thank the Scientific Committee for their invaluable role in making the conference a success and producing this book Chapter 1

INTRODUCTION

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Abstract

The motivation for the book and its individual chapters are briefly discussed.

1. Motivation for the book and its individual chapters

The IUTAM Symposium on Flow in Collapsible Tubes and Past Other Highly Compliant Boundaries was held on 26-30 March, 2001, at the University of Warwick. As this was the first scientific meeting of its kind we considered it important to mark the occasion by producing a book. Accordingly, at the end of the Symposium the Scientific Committee met to discuss the most appropriate format for the book. We wished to avoid the format of the conventional conference book consisting of a large number of short articles of varying quality. It was agreed that instead we should produce a limited number of rigorously refereed and edited articles by selected participants who would aim to sum up the state of the art in their particular research area. The outcome is the present book.

There are numerous physiological examples of compliant tubes which collapse because the internal-external pressure difference falls below a critical value close to zero. In such cases the cross-sectional area varies significantly in response to the dynamics of the internal flow (e.g., veins above the heart, arteries under a cuff, large airways in forced expiration, and the urethra during micturition). Laboratory experiments using rubber tubes of finite length reveal a rich variety of self-excited oscillations, indicating a complex underlying dynamical system. Theoretical models have been developed of zero, one, and two space dimensions, including a complete numerical simulation of a realizable two-dimensional system. Nevertheless, the mechanism of the oscillations (the structure of the dynamical system) is still poorly understood despite recent progress. It has been proposed both at the Symposium and previously that the oscillations are 'merely' the result of a hydroelastic instability. But the analogy is certainly not exact because most flutter theories analyse the instability of a parallel undisturbed flow state whereas in very compliant tubes the steady state from which oscillations develop is highly deformed.

More generally there are many other biomechanical, biological and engineering examples of external and internal flows past highly compliant boundaries (e.g., mechanics of snoring, pressure pulse propagation in the cerebrospinal-fluid system in the spine, hydrodynamics of dolphins and other aquatic animals, drag reduction, process engineering, and structure-borne sound). The underlying physical phenomena and mathematical modelling have much in common with those applicable to collapsible tubes. Nevertheless, until the IUTAM Symposium there had been little exchange of ideas between the researchers working in the various areas. Certainly, as this book will make clear, much progress has been made towards a fuller understanding of the interaction of flows with highly compliant boundaries. Nevertheless, many unanswered questions remain. In particular, significant contradictions remain unresolved between the theoretical, computational-simulation and experimental approaches. In addition, much remains to be learnt about nonlinear effects, particularly from a dynamical systems perspective. Recent progress towards understanding the effects of wall compliance on turbulent flow was reported at the Symposium and this, too, is reflected in the present book. It still remains true, however, that the physics involved is poorly understood.

The main part of the book is divided into three sections: A. Collapsible Tubes, B. Instability of Flow Past Compliant Walls, and C. Drag Reduction and Turbulence Modification.

A. FLOW IN COLLAPSIBLE TUBES

A collapsible tube is an elastic tube that is subjected to an external pressure large enough to cause its cross-section to deform significantly in both shape and area, thereby becoming so compliant that flow-induced internal pressure changes can couple strongly to the wall-deformation. The first of the two chapters in this volume on flow in collapsible tubes, chapter 2, is much longer than most of the chapters in this book because the two authors, M. Heil and O. E. Jensen, (with the editors' enthusiastic agreement) decided to join forces and provide a substantial review of both the biological applications (and motivation) of the field and the current state of theoretical modelling. Among other things, they survey applications to:

- blood flow in the cardiovascular system, notably systemic arteries that collapse under a sphygmomanometer cuff, dynamic flow-induced collapse of arteries downstream of atherosclertic stenoses, veins above the level of the heart (notably the jugular veins of a giraffe), and limb veins subjected to external compression in order to inhibit deep vein thrombosis in the bedridden.
- Urodynamics: the urethra collapses during micturition, and the ureters, like the gut, are squeezed by contraction of the smooth muscle in their walls, leading to peristaltic pumping of their contents.
- Air flow in the lungs, where the larger intrathoracic bronchi collapse during forced expiration, sneeze, or cough, and parts of the upper airways (e.g. soft palate and pharynx) of some subjects collapse during respiration, causing snoring. The vocal cords can also be thought of as a collapsible tube in which self-excited oscillations arise.

The relevant presentations at the IUTAM Symposium, referred to in the chapter, were by B. S. Brook and T. J. Pedley (giraffe jugular vein), T. S. Balint and A. D. Lucey (snoring), J. L. van Leeuwen (phonation in birds) and K. Berkouk, P. W. Carpenter and A. D. Lucey (pressure waves in the cerebrospinal fluid system in the spine).

Most of the chapter, however, concerns the theoretical modelling. The authors review the major theoretical and computational developments of the past twentyfive years, with particular focus on the development of self-excited oscillations: lumped-parameter models, one-dimensional models, and the most recent two- and three-dimensional models and simulations. Not content with surveying what has gone before, the authors also provide a taste of the new modelling that is currently in progress, notably by themselves (separately and together) and by X. Y. Luo and T. J. Pedley and their colleagues. The presentations from the Symposium that feature here are the separate ones by O. E. Jensen and M. Heil, and those by Z. X. Cai and X. Y. Luo, T. J. Pedley (and J. C. Guneratne), and C. Davies and P. W. Carpenter.

Chapter 3, by C. D. Bertram, is a wide-ranging historical review of the literature on observations and experiments in collapsible tubes. It begins with the early records of venous collapse by Valsalva around 1700, and the first observations of self-excited oscillations (in the jugular vein of the horse) by Barry in 1824, but notes that the first, or at least most famous, early use of a short length of non-biological collapsible tube in a biomedical context was that by Starling in 1914, giving rise later to the name "Starling resistor" for the standard collapsible tube experimental apparatus. The chapter explains the differences between early experiments, not always fully recognised by the experimenters, and outlines all the major features that experimentalists (notably Dr Bertram himself) have since sought to measure and to understand:

- the elastic properties of collapsible tubes, often assumed to be given by a "tube-law" relating transmural pressure to local cross-sectional area, and the problems of measuring either pressure or area;
- flow patterns in collapsible tubes, notably flow separation and its importance or otherwise in the generation of self-excited oscillations;
- choking, when the fluid speed becomes equal to the wave speed, and whether the existence of supercritical flow is necessary for self-excited oscillations;
- flow limitation and pressure-drop limitation;
- collapsible stenoses (cf chapter 2);
- collapsible tubes as complex nonlinear dynamical systems.

The chapter concludes with a brief survey of biomedical applications. The presentations from the Symposium that are referred to here are those by K. Ohba et al, by Y. Matsuzaki et al and by C. D. Bertram and N. S. J. Elliott.

B. INSTABILITY OF FLOW PAST COMPLIANT WALLS

This section begins with Chapter 4 – an account of convective and absolute instabilities in flow over compliant walls by C. Davies. For such systems both the fluid flow and the flexible wall are wave-bearing media. The result is the rich spectrum of eigenmodes that is reviewed in this chapter. This proliferation of eigenmodes greatly increases the opportunities for modal interaction and coalescence, making absolute instability far more likely. Much recent progress has been made in understanding the flow physics involved.

Chapter 5 by V. Kumaran describes the recent progress towards understanding the hydrodynamic stability of flow through compliant pipes. Again there is a bewildering variety of different disturbance types that can become unstable. These are described and explained in this chapter.

The complexity of the eigenmode structure and the rich variety of wave types that are so much a feature of the previous two chapters have motivated various approaches and applications. For example, many of the problems studied in the context of structure-borne sound evidently have a close connection to those studied for other applications of compliant walls. In Chapter 6 A.D. Lucey and N. Peake review the recent work of this type on wave excitation of flexible walls in the presence of a fluid flow. Model problems that have been fairly widely studied involve the response of various flexible surfaces to impulsive and harmonic forcing in the presence of a fluid flow. In fact, the impulsively driven flexible plate was one of the very first systems in fluid dynamics to be analysed (Brazier-Smith & Scott 1984) by using the approach of Briggs (1964) and Bers (1983). The corresponding problem with harmonic forcing was initiated by the seminal paper of Crighton & Oswell (1991).

Much of the theoretical work on waves propagating in flows over compliant and other flexible surfaces is based on the assumption of an infinitely long surface. Plainly in real applications and in experimental studies the flexible surfaces are of finite length. Nevertheless, until recently little was known about the behaviour of vortical waves (such as Tollmien-Schlichting waves) when incident on junctions between rigid and compliant walls. The theoretical analysis of longitudinal waves incident on junctions in flexible tubes is well-known and well-understood; see, for example, Lighthill (1978). But these waves are not vortical and the conservation principles applied at the junctions do not generalize to vortical waves. These were apparently first investigated in the numerical-simulation study of Davies and Carpenter (1997). They noted that when a Tollmien-Schlichting wave was incident on the leading edge of a finite compliant panel, its response appeared to correspond to a complex superposition of various eigenmodes of the infinitely long fluid-flow/compliant-wall eigensystem. Given this, the key question is: how do you relate the amplitudes and phases of the eigenmodes on either side of a junction? This question has been investigated by several authors recently and their work is reviewed by P.W. Carpenter and P.K. Sen in Chapter 7.

The compliant disc rotating in water that is otherwise still until disturbed has been the basis of compact and relatively simple apparatus for many investigations into drag reduction and transition delay by compliant walls. Usually in such investigations only the speed of rotation and the driving torque are measured. And, until recently, little was known about the effects of wall compliance on the nature and behaviour of the disturbances in the rotating-disc boundary layer. Over the past few years these disturbances have been extensively investigated in a series of theoretical, computational and experimental studies, mostly carried out at the University of Warwick. This work and the earlier experimental studies are reviewed in Chapter 8 by P.W. Carpenter, P.J. Thomas and M. Nagata. They also review the recent work on the effects of wall compliance on thin-gap rotating flows, done at Marseille, and on Taylor-Görtler instabilities, particularly the recent work at Kyoto on the stability of Taylor-Couette flows.

C. DRAG MODIFICATION AND TURBULENCE MODIFICATION

There are many different, multi-disiciplinary aspects to an assessment of the potential of compliant walls for drag reduction and turbulence modification. In an extended version of his key-note lecture, these are reviewed in Chapter 9 by M. Gad-el-Hak with an emphasis on the practical engineering issues involved.

As will have been made clear in the previous chapter, the effects of wall compliance on flow stability and laminar-turbulent transition are now well-understood.

Furthermore, there is now good agreement between experimental measurements and theoretical predictions. In contrast, our understanding of the effects of wall compliance on turbulent flows is still rather poor. There is a wealth of experimental evidence, much of it from Novosibirsk (Semenov 1991) and Kiev (Babenko et al. 1993), that substantial drag reduction and turbulence suppression is possible by use of compliant walls. But we still lack a firm theoretical basis for understanding how wall compliance can modify turbulent flow. For example, it seems from the work of Semenov and others that flexible walls orders of magnitude stiffer than the original compliant coatings of Kramer (1957, 1960) are capable of substantially reducing the level of turbulence and skin friction. Yet, much more flexible walls, similar to those of Kramer, also appear to possess such a capability. This apparent paradox is still unresolved. There has been some recent progress towards a theoretical understanding of the effects of wall compliance on turbulence and this is reviewed in Chapter 10 by D. Rempfer, L. Parsons, S. Xu and J. Lumley. One aspect of the interaction of a flexible wall with turbulent flow that has become better understood in recent years is the effects of turbulence on the flow-induced surface waves. The recent progress on this topic is reviewed by K.-S. Yeo in Chapter 11, while in Chapter 12, K.-S. Choi reviews the recent experimental research on turbulent flow over compliant walls.

Research on the use of compliant walls for drag reduction and laminar-flow control was originally inspired by studies of dolphin hydrodynamics. First there was the study by Gray (1936) of the energetics of dolphin propulsion. Gray concluded that if conventional hydrodynamics were involved, the power output per unit mass of dolphin muscle would need to exceed the mammalian norm sevenfold in order to propel the animal at the swimming speeds commonly observed. This became known as *Gray's Paradox*. It and the remarkable drag reductions achieved by Kramer (1957, 1960) with his artificial dolphin skin led to the many subsequent investigations of the drag-reducing and laminar-flow capabilities of compliant walls. Accordingly, it seems fitting to end the book with a re-assessment of Gray's paradox and review of dolphin hydrodynamics by V.V. Babenko and P.W. Carpenter.

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Appendix

List of presentations at the IUTAM Symposium on Flow in Collapsible Tubes and Past Other Highly Compliant Boundaries 26-30 March, 2001, University of Warwick

The number in square brackets refers to the chapter in which the work presented is described and discussed.

Flow in Collapsible Tubes

M. Heil, University of Manchester, U.K.Keynote Lecture: Flow in collapsible tubes: The biomechanics perspective.[2]

C.D. Bertram and N.S.J. Elliott, University of New South Wales, Australia. Comparison of flow limitation in one tapered and two uniform collapsed tubes. [2, 3]

B.S. Brook¹ and T.J. Pedley² ¹University of Sheffield; ²University of Cambridge, U.K. The effect of non-uniform mechanical and elastic properties on steady and time-dependent flow in (giraffe jugular) veins. [2]

J.C. Guneratne, G. Picard and T.J. Pedley, Cambridge University, U.K. High-Reynolds-number asymptotics for flow in collapsible channels and tubes. [2]

Z.X. Cai¹, X.Y. Luo¹ and T.J. Pedley²
¹University of Sheffield; ²Cambridge University, U.K.
A localized asymptotic solution for a fluid-beam problem. [2]

Z.X. Cai and X.Y. Luo, University of Sheffield, U.K.

A fluid-beam model for collapsible channel flow. [2]

M. Hamadiche¹ and M. Gad-el-Hak² ¹École Central de Lyon, France; ²University of Notre Dame, U.S.A. Stability of collapsible ducts. [2]

O.E. Jensen, University of Nottingham, U.K. Self-excited oscillations in an elastic-walled channel: insights from a simple asymptotic model. [2]

K. Ohba, T. Kamimura, K. Bando and K. Hanazono, Kansai University, Japan.

Distribution of flow velocity and pressure in a largely deformed collapsible tube. [3]

R.A. Scroggs, E.A. Patterson and S.B.M. Beck, University of Sheffield, U.K. Numerical fluid-structure interaction model of a collapsible tube using LS-DYNA. [3]

Biomechanical Applications

T.S. Balint and A.D. Lucey, University of Warwick, U.K. Instability of a flexible cantilevered plate in plane channel flow. [2]

M. Bathe, A. Shirai and R.D. Kamm, M.I.T., Cambridge, Mass., U.S.A. Numerical simulation of neutrophils and other highly compliant cells. [2]

K. Berkouk, P.W. Carpenter and A.D. Lucey, University of Warwick, U.K. *Pressure propagation in the spinal CSF system.* [2]

P.W. Carpenter, University of Warwick, U.K.Does the dolphin have a secret? The hydrodynamics of dolphin skin re-visited.[13]

M. Heil and J.P. White, University of Manchester, U.K. Airway closure: surface-tension-driven non-axisymmetric instabilities of liquid-lined elastic tubes. [2]

J.L. van Leeuwen and C.P.H. Elemans, Wageningen University, The Netherlands.

A biomechanical model of vocalisation in birds. [2]

Y. Matsuzaki, M. Watanabe, T. Aomatsu and T. Ikeda, Nagoya University, Japan.

Experiment on flow in a two-dimensional channel with an obstruction oscillating in high frequency: Preliminary study. [2, 3]

Effects of wall compliance on boundary-layer stability and transition

M. Gad-el-Hak, University of Notre Dame, U.S.A. Keynote Lecture: Compliant coatings – What works and what doesn't? [9]

V.V. Babenko, Institute of Hydromechanics UAS, Kiev, Ukraine. External and internal flows on elastic surfaces. [13]

A. Cros¹, R. Ali², L. Schouveiler¹, P.J. Thomas², P. Le Gal¹, M.-P. Chauve¹, P.W. Carpenter² and C. Davies³ ¹IRPHE, Marseille, France; ²University of Warwick; ³ Cardiff University, U.K.

Transition of torsional Couette flow between a compliant rotating disk and a stationary rigid wall. [8]

S. Manuilovich, Central Aero-Hydrodynamics Institute (TsAGI) Moscow, Russia.

Propagation of Tollmien-Schlichting wave in a boundary layer over a flexible path of a wall. [7]

Effects of wall compliance on turbulence

K.S. Choi¹, E. Le-Hou¹, B.R. Clayton¹ and M.P. Escudier² ¹University of Nottingham; ²University of Liverpool, U.K. *Turbulent boundary-layer structure over a compliant surface.* [12]

E.R. Fitzgerald, Johns Hopkins University, U.S.A. Influence of viscoelastic material properties on turbulent flow past thin compliant walls. [8, 13]

V.M. Kulik and S.L. Morosova, Institute of Thermophysics RAS, Novosibersk, Russia. Response of a compliant coating to fluctuating wall pressure. [12]

L. Parsons¹, D. Rempfer² and J.L. Lumley¹ ¹Cornell University; ²Illinois Institute of Technology, U.S.A. Low-dimensional model of the interaction of near-wall turbulence with a compliant boundary. [10]

V.P. Reutov and G.V. Rybushkina, Institute of Physics RAS, Nizhny Novgorod, Russia.

Nonlinear dynamics of hydroelastic waves in a turbulent boundary-layer flow past a compliant wall. [11]

B. Semenov, Novosibersk, Institute of Thermophysics RAS, Novosibersk, Russia.

Interference action of compliant boundaries on flow in collapsible tubes. [10, 12]

S. Xu¹, D. Rempfer² and J.L. Lumley¹

¹Cornell University; ²Illinois Institute of Technology, U.S.A. Direct numerical simulation of the interaction of near-wall turbulence with a compliant wall. [10]

K.S. Yeo, H.Z. Zhao and B.C. Khoo, National University of Singapore. Turbulent flow over a compliant surface – wave instabilities. [11]

Flow-induced waves over flexible walls

C. Davies¹ and P.W. Carpenter²
¹Cardiff University; ²University of Warwick, U.K.
Numerical simulation of instabilities in boundary layers over a compliant wall.
[4]

U. Ehrenstein¹ and O. Wiplier² ¹Université de Nice-Sophia Antipolis; ²Université de Lille, France. Local and global stability behaviour in a boundary-layer flow with compliant coatings. [4, 7]

E. de Langre, LadHyX, Ecole Polytechnique, France. The effect of structural characteristics on the onset of absolute instability in compliant structures submitted to inviscid flow. [6]

A.D. Lucey, University of Warwick, U.K.Wave excitation and the destabilisation of a flexible surface by a uniform mean flow. [6]

N. Peake, Cambridge University, U.K. Nonlinear stability of a fluid-loaded elastic plate with mean flow. [6]

P.K. Sen¹, P.W. Carpenter², J.S.B. Gajjar³ and S. Hegde¹.
¹IIT Delhi, India; ²University of Warwick; ³University of Manchester, U.K. *The jump conditions for instability waves at a rigid-compliant joint.* [7]

10

Internal flows with compliant walls

M. Gad-el-Hak¹ and M. Hammadiche² ¹University of Notre Dame, Indiana, U.S.A; ²École Centrale de Lyon, France. *Temporal stability of flow through viscoelastic tubes.* [5]

J.S.B. Gajjar¹, A. Gibson¹ and P.K. Sen² ¹University of Manchester, U.K.; ²IIT Delhi, India. Instabilities in compliant pipes and related flows. [5]

S. Koga and M. Nagata, Kyoto University, Japan. Stability of Couette flow with a compliant cylinder. [8]

V. Kumaran, Indian Institute of Science, Bangalore, India Classification of instabilites in flow past flexible surfaces. [5]

M. Tamilarasan and K.-S. Choi, University of Nottingham, U.K. Drag reduction in turbulent pipe flows using compliant coating. [12]