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INTERNATIONAL CENTRE FOR MECHANICAL SCIENCES

COURSES AND LECTURES - No. 528

REDUCED-ORDER MODELLING FOR FLOW CONTROL

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SpringerWienNewYork

This volume contains 101 illustrations

Printed in Italy
SPIN 80061174

All contributions have been typeset by the authors.

ISBN 978-3-7091-0757-7 SpringerWienNewYork

FOREWORD

Practical interests in flow control have no longer to be demonstrated. Flow control has motivated rapid developments in the past two decades in experiments, flow stability theory and computational fluid dynamics (CFD). Recent advances in experimental studies include applications of more and more sophisticated actuators and sensors. However, up to now, most of the results are predominantly related to open loop, at most, adaptive approaches. Early closed-loop applications of control methods were in noise control based on anti-noise concepts. These studies established the pioneering link between fluid mechanics and control theory. However, in most aerodynamic applications, turbulent flows are encountered. Due to the intrinsic nonlinearities, turbulence gives rise to a large variety of temporal and spatial scales of more or less organized nature. Turbulence has remained one of the last not satisfactorily resolved physical phenomenon of practical importance in engineering sciences. It is obvious that the complexity of these flows is so pronounced that simpler – if this term can be used for turbulent flows – descriptions need to be derived.

The encountered complexity is observed at three levels. First, the characterization of the flow itself is complex and depends on the type of available information (e.g. sensors). Any state information is by nature incomplete or of excessive extent for turbulent flows. Second, the effect of any actuator is by nature 3D and unsteady, thus difficult to characterize. Third, the complete modelling of the flow (CFD), its sensitivity to perturbations, etc. exceeds available computer power by many orders of magnitudes, particularly for online capability in experiment. In the same vein, the predominantly (locally) linear approaches of control theory need to be adapted to the reality of the complex, turbulent flow characteristics. This leads to different levels of fluid mechanics one has to take into account. These levels can start from a detailed fluid mechanics characterization, including the more or less organized nature of the turbulent flows, the so called white-box model and end with entirely black and eventually 'empty-box' models.

The communities of flow control, applied mathematics and turbulence in fluids have then to work altogether in a close manner. Each domain enriches the other for the dedicated goal of controlling different types of flows. No currently available approach can be re-

tained, due to the variability of the physics to be controlled (e.g. flow separation, drag, lift, mixing, noise generation and fluid structure interactions). The present volume is written by leading experts of flow control and represents the state of the art of the different approaches whose complementarity will open new areas by mutual fertilization.

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PREFACE

Active turbulence control is a rapidly evolving new field of fluid dynamics with large industrial importance. Several developments serve as catalyzers. Actuators and sensors have become increasingly more powerful, cheaper and more reliable to be considered for practical applications. In fact, aeronautic, car and other transport-related industries work at active turbulence control solutions for selected demonstrators. Examples are the high-lift configuration of an airfoil or drag reduction of cars. The past stigma of active control as proof of a inferior aerodynamic design is replaced by the realization that active control is a critical enabler for future performance enhancements. Not much phantasy is required to envision a not-too-far future in which active control will be commonly seen on cars, trains, airplanes, helicopters, wind energy plants, air-conditioning systems, and virtually all flow related products. Active turbulence control is having an impact of epic proportions.

Active control requires at minimum parameter adjustments for flow conditions and occasionally in-time response using flow sensors. Hence, active control generally requires — or at least benefits — from a closed-loop scheme for optimal performance. Closed-loop control has clearly been demonstrated to be superior to (blind) open-loop control in many cases. Performance of closed-loop control does not only depend on the chosen actuators and sensors. It critically depends also on the control logic with its underlying model.

Model development and control design for closed-loop flow control is the focus of this book. Wiener (1948) discriminates between black-, grey-, and white-box models. The black-box models identify the dynamics between the input (actuation) and the output (sensing) from data — ignoring any other aspect of the flow. The white boxes represent the full-state representation, here: Navier-Stokes discretizations. And the grey boxes resolve a small yet relevant portion of the full state dynamics, here: the evolution of coherent structures. All models have their relative merits and shortcomings. Black-box models represent the behavior of experiments with accessible accuracy. On the downside, physical understanding of coherent structures and associated nonlinearities is discarded. Navier-Stokes discretizations are accurate representations of the flow but come with a large com-

putational load. This computational expense is a large challenge for control design and too large for any foreseeable operation in experiments. Reduced-order models for the coherent-structures are a good compromise between required resolution and necessary simplicity for online-capability in experiment. Their price is a large experience in model development. For later reference, we add to Wiener's classification model-free approaches (or 'empty boxes') which make only qualitative assumptions about the dynamics.

The authors describe the current state on closed-loop flow control from various, necessarily biased experimental and computational angles. In particular, we have attempted to provide a book with elementary self-consistent descriptions of the main methods. Thus, our book may serve also as guide through the large jungle of myriad of publications in the field. Topics include the complete span of flow control based on white-box models (first two chapters), grey-box models (second two chapters) and black- to empty-box models (final two chapters):

These lecture notes originate from a course held at the Centre International des Sciences Mécqniques (CISM) in Udine, Italy in September 2008. The Editors thank Prof. W. Schneider for the kind invitation to this course. We thank the CISM staff and the Rector Prof. G. Maier for dependable, professional support in all technical aspects of the course. The beautiful city of Udine, the cooperating late-summer weather, and the magnificent Palazzo del Torso provided the perfect forum for many memorable interactions during class-room time, breakfast, lunch and dinner. We thank the authors for their excellent lectures and equally illuminating chapters. Each chapter condenses a long-term research and teaching effort of the corresponding authors. We thank the participants for coming with large curiosity and penetrating questions, making our course a lively worthwhile event.

Poitiers, Poznań and Boston in February 2010
Bernd Noack, Marek Morzyński and Gilead Tadmor
on behalf of the whole co-author team

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