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DCT 2003.86

DCT report

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Eindhoven, September, 2003

1 Introduction

In this report I will give an overview of my trip to the USA in June 2003. During this three week visit I attended the American Control Conference, the Turbo Expo 2003, and I visited the Gas Turbine Laboratory of the MIT.

The ACC was organized very well and the atmosphere at the conference was pleasant and informal, which gave me a good chance to meet a lot of people in the control engineering community. The quality of the presentations—both the contents and the oral presentations—at the ACC was very diverse, not in the last place caused by the absence of many principal authors.

For the Turbo Expo the same comments can be made about the organization and the quality of the papers. Due to the combination of a technical congress, a user's symposium and an exhibition the Turbo Expo was a much larger scale meeting than the ACC. This made it less easy to get in contact with people with the same scientific interests. Overall, both conferences gave me a good idea of what to expect from a scientific conference in general, the quality of the presented work and the opportunities to extend contacts with people from the scientific community.

The visit to the MIT was a very informal one and the agenda of my visit was made up when I was already there. The work that is done at the GTL is mainly focussed on modelling of phenomena in turbo machinery. Experimental work is mostly performed in collaboration with, and at laboratories of NASA and various (aerospace) companies in the US. The presentation of my own work was received well and finally, the visit provided some useful contacts and the possibility for collaboration during some parts of my research in the future. Now I have become acquainted with the GTL, it should be easier to make a more detailed and better prepared appointment, whenever another opportunity arises to visit the GTL again.

2 American Control Conference

The 2003 American Control Conference was held on June 4–6 in Denver, Colorado. It included 947 invited and contributed papers, 3 plenary lectures and various other sessions and workshops. The ACC aims to reflect the continued interest in the field of control engineering and its applications in emerging technologies and theoretical developments that are needed to meet the ever increasing demands placed on control systems. The variety of program sessions was large, ranging from basic control theory to industrial applications. Here, an overview will be given of some of the interesting presentations that I have attended.

2.1 Constrained nonlinear systems

In the session 'Constrained nonlinear systems I' various inventive techniques were presented that deal with constraints during the controller design. The session covered the whole spectrum of the topic, from the development of new mathematical theory to practical solutions to get around problems in industrial applications. Two presentations that belong in this last category showed that it is worthwhile to look for solutions from linear systems and control theory to deal with problems in constrained nonlinear control.

In [1] the problem of controlling nonlinear systems with large operating ranges was solved by designing a set of local output feedback predictive controllers with their estimated regions of stability covering the desired operating region. These controllers were then implemented as a single scheduled output feedback MPC that switches on-line between the set of local controllers while achieving nonlinear transitions with guaranteed stability.

A simple and pragmatic solution of dealing with input constraints was presented in [2]. The authors used a linear algebraic equivalence of the required nonlinear controller and based on this equivalence, well-known techniques like quadratic programming and constraint linear least squares methods could be utilized to design a controller. The technique was illustrated in a case study of an ill-conditioned thermal heating system that should impose a given temperature profile on a design surface.

2.2 Stability of time delay systems

Two different sessions dealt with the stability of time delay systems. The papers of the first session were all very theoretical in nature. In [3] the problem of stabilizing linear systems with state and input delay was addressed. First the authors applied a system transformation to obtain an equivalent input delay free system. The main contribution of the paper was the development of a set of sufficient conditions for asymptotic stability when the transformed system is controlled with a sliding mode controller. In the second session on this topic another problem for a similar system is addressed in [4]. The paper presents a robustification algorithm for an optimal regulator based on integral sliding mode compensation of disturbances. In an example it was shown that the addition of the designed integral sliding mode regulator effectively suppressed external disturbances that otherwise would have deteriorated the performance of the optimal regulator.

2.3 Fluid systems

Two papers in the session on fluid systems were of special interest to me given the topic of my own research. The topic of [5] was the development of a dynamic model of a jet actuator used to influence the flow over an airfoil. Recently, the technique of air injection has been of particular interest in the area of active stall control in turbo compressors. In the mentioned paper however, no attention was paid to the interaction of the ejected jets with the flow around the airfoil. The authors mainly focussed on developing a dynamic model of the crankshaft and other mechanical components that were used to drive the jet actuator. The discussed techniques could be found in every textbook on dynamic modelling so, besides the technological news that a new jet actuator was developed, the paper offered no serious scientific developments at all.

The sixth paper was of particular interest since it discussed the semi-global output feedback stabilization of compressor stall dynamics [6]. The paper was presented by a colleague of the authors so the discussion after the presentation was fairly superficial. The system dynamics that had to be stabilized were described by a Moore-Greitzer model, where the compressor characteristic was described by a third-order polynomial which is the standard technique in simulation studies of rotating stall and surge. The authors designed a two-state-feedback backstepping controller to stabilize the Moore-Greitzer model in combination with a nonlinear high-gain observer to estimate the mass flow through the compressor from measurements of the pressure rise across it. With Lyapunov techniques the authors computed an explicit lower bound on the observer gain such that the specified equilibrium was asymptotically stable for the closed-loop system with a domain of attraction that contains the specified inner bound of this domain of attraction. Simulation results showed that the applied controller and observer were able to prevent rotating stall and surge from occurring. Although the idea of applying a mass flow observer to circumvent the problems of applying state-feedback is not new, the rigoureus theoretical treatment and the presented simulation results gave a good idea of the possibilities of this technique. The authors however did not question the applicability and the validity of the used Moore-Greitzer model for describing real compressor systems. Therefor more research would be required in order to successfully implement the presented techniques in practice.

2.4 Fault detection

The conference offered several sessions on fault detection. A paper of particular interest given my MSc project on fault detection and classification in optical disc drives, was the paper on optimal treshold functions for fault detection and isolation [7]. Fault diagnosis systems usually comprises a filtering part and a decision part. In the filtering part a signal is constructed that is indicative for the presence or absence of the type of faults that are to be detected. In the decision part this signal is compared to a certain threshold in order to decide whether a fault occurred or not. In this paper the authors presented a systematic way to select a threshold level that optimizes the chances on making a false positive and a false negative decision. The method is based on the balance between the probability of the two mentioned false decisions for a given signal-to-noise ratios.

In [8] a robust method was presented to obtain a residual signal that is indicative for a fault in a periodic system under the influence of external disturbances. The method was based on a H_2 estimation approach where the faults are considered as inputs to the system. By applying well-known concepts from H_2-theory the specified system could be written in a form that provided the required residual signal or, in other words, an optimal estimation of the fault signal. The main drawback of the presented method was the very restrictive assumption for the occurring disturbances, namely that they could be represented by constant signals. In the presented simulation results the applied fault for testing was also a constant signal, so the applicability of the method for more realistic situations remained unclear.

A similar remark could be made on the method presented in [9]. Here the authors presented another robust fault detection method that was able to detect multiple faults simultaneously. The method however required detailed knowledge of the fault dynamics in the form of a transfer matrix. The performance of the method in the presence of large uncertainties in those fault dynamics was not yet investigated. The idea that determining these fault dynamics formed the core of the whole fault detection problem, was not really underwritten by the author during the discussion after the presentation.

3 MIT Gas Turbine Laboratory

On 9 and 10 June I visited the Gas Turbine Laboratory of the Massachusetts Institute of Technology. For over fifty years the GTL has worked on the modelling and control of turbo machinery. In their research they focuss mainly on developing physical models of various turbine and compressor components and on first principle models that are able to describe the global (stable and unstable) behavior of turbo machinery.

During my visit I spoke with J. D. Paduano, a principal research engineer at the GTL who has been involved in various projects on active control of surge and rotating stall. Over the last years the GTL has collaborated closely with the NASA Glenn Research Center on active rotating stall control. Currently this research has reached the phase in which the developed concepts are ready for implementation and experimental evaluation. This part of the work is mainly continued at NASA Glenn.

Next to a fruitful discussion on the current issues of active stall control, I received some useful information on the results that have been obtained at the GTL. I also got some names of people from valve manufacturers that can possibly assist in supplying or designing fast control valves. Next I got a tour through the laboratorium of the GTL. They have two large turbo installations available that are used for compressor and turbine experiments. Both facilities are so-called blowdown systems that can only be operated for a very short time due to the limited amount of compressed air that is available. Both facilities are heavily equipped with sensors and actuator valves, mainly used for rotating stall measurements and control experiments. Next to these installations, there were various other small scale facilities available. Although most of the equipment was still used in ongoing research the overall picture of the laboratorium was that it looked somewhat worn and out of date. The newest facility, a new compressor installation, was still in the early stage of development. This general impression matched with the fact that the research at the GTL is mainly of a theoretical nature. Especially for the compressor control research the GTL heavily relied on the experimental facilities at the NASA Glenn Research Center.

In a discussion with Shengfan Liao, a research assistent at the GTL I talked about extending compressor models to take the effects of bleed valves into account. In his PhD research he worked on robust control of rotating stall by using various bleed valves around the circumference of the compressor exit ducting [10]. In his thesis some interesting information can be found on describing compressor disturbances and include them in the compressor models, used for controller design.

The most fruitful discussion however was with Z. S. Spakovszky. As an associate professor he has been extensively involved in the recent projects on active rotating stall control. During his PhD research he developed a modular compressor model by applying first principle modelling to the various compressor components [11]. This modelling approach was then used to investigate the phenomenon of backward travelling rotating stall waves that where detected during experiments at the GTL. Simulations with this model showed that air injection in the vaneless space between the compressor impeller and diffusor could suppress surge and rotating stall up to 20% lower mass flows than without control [12]. Experiments at NASA Glenn verified these findings on an experimental high-speed compressor. The advise that he gave me, based on is own experience, was that the most important first step is to find out how and where the instabilities arise and how they could be modelled correctly. For this analysis it is crucial to instrument the compressor with numerous sensors and implement a way to do forced-response experiments on the installation. The resulting data should give the insight into the inception mechanisms of surge and rotating stall and the interaction between both phenomena. With this knowledge it should then be possible to develop an accurate compressor model, which then could be used to design sensible control strategies.

At the end of my visit to the GTL a colloquium was organized during which I gave a presentation about the 'Control of compressor surge with rotating stall' project. After a short introduction and an overview of the organization and goals of the project, I presented the preliminary results of my incipient surge detection research. The discussion that followed was mainly about the scepticism whether these results could lead to a generally applicable incipient surge detection algorithm. In the last part of my presentation I talked about the plans to implement the one-sided surge control strategy. Although their own focus is on rotating stall control, the attendants all showed great interest in these plans to implement an active surge controller on such a large compressor installation.

The overall conclusion on this visit is that it was very useful. The other way of looking at the problem gave me some interesting new ideas for my research, especially on the modelling and analysis of the compressor system and the occurring instabilities. Both James Paduano and Zoltan Spakovszky would like to maintain contact and hear about our progress and perhaps even collaborate in our work on the large scale experimental facility.

4 Turbo Expo

The ASME Turbo Expo 2003 was held on June 16–19 in Atlanta, Georgia. This conference consisted of a technical congress, a user's symposium and an exhibition. It included 227 paper sessions, 2 keynote sessions and various other sessions and workshops. The Turbo Expo aims to cover the whole spectrum of turbo machinery issues, ranging from scientific and technological advancements to practical problems during operation and the availability of new hardware for the industry. Here, an overview will be given of some of the interesting presentations of the technical congress that I have attended.

4.1 Diagnostics

One of the topics of the congress was the controls, diagnostics and instrumentation for turbo machinery. In [13] a method is described to monitor the engine performance on-line. This monitoring is carried out through an engine health parameter estimation, based on several gas path measurements. This health parameter estimation makes use of an engine model and therefore knowledge of the engine state is required. The estimation of the engine states is carried out by an extended Kalman filter, while the health parameter estimation is done by solving a classical recurrent regression problem. The paper shows that by using so-called dual Kalman filters both problems can be solved simultaneously and that this approach provides the necessary robustness for faulty data.

A more general diagnostics approach is presented in [14]. Here a framework is presented that enables the combination of computerized maintenance management systems (CMMS), enterprise resource management (ERM) and planning (ERP) with condition based maintenance (CBM) data. Finally, various fault detection and diagnostics methods are discussed that could be implemented within the overall framework. The focus of this paper was mainly on the promotion of the MIMOSA system that provides a platform for the integration of all the mentioned technical and business support systems.

4.2 CFD

Numerous papers dealt with CFD simulations of various flow problems and the obtained results. In [15] a comparison was made between classical calculation methods for bearing and damper analysis and the results obtained with CFD simulations of these elements. For various types of bearings and dampers calculations and simulations are performed. For many cases the results obtained with both methods are very similar, indicating that CFD can be suitable for bearing and damper analysis. However in some cases the authors observe differences up to 50% between the classical numerical solutions and the CFD results. Without a doubt they conclude that CFD is therefore a much better tool in those cases. However, no experimental validation is performed that confirms the correctness of the CFD results. The audience therefore remained sceptical during the discussion about the presented conclusions.

The aerodynamic analysis of a multi-stage centrifugal compressor by using CFD was discussed in [16]. The authors presented their results of a three-dimensional multistage CFD code and compared them with results for various single stage and component simulations. Based on the results of this comparison and the good agreement with experimental data the authors concluded that single stage simulations are usually sufficient. Furthermore their comparisons showed that several parameters and boundary conditions had little or no influence on the results, and therefore could be neglected.

4.3 Blading

Various papers discussed the design and analysis of airfoils and rotors for turbo machinery. In [17] a very straightforward approach was presented to design a blade profile with less flow separation at the upper trailing edge of the blade. The authors concluded that the occurrence of blade stall is related closer to the moment coefficient than to the lift coefficient. In the new airfoil design the constant moment coefficient is extended to a higher angle of attack region, which will delay the upper trailing edge separation to a higher angle of attack, the main source of rotating stall.

In [18] the aerodynamic and aeroacoustic behavior of a forward skewed rotor is investigated and compared with unskewed rotor blades. The three-dimensional flow field in the inter-blade row and passage is investigated both by experiments and simulations. The results show that the skewed rotor results in an increased pressure rise, a larger flow rate, and a higher efficiency. This is due to the advantageous spanwise redistribution of aerodynamic parameters, a greater boundary movement into the main flow, a secondary flow reduction, and the thinness of the rotor wake. The aeroacoustic experiments show a decrease in noise levels in almost the whole frequency range, due to a smaller wake layer, a phase difference in rotor radiation, and tip leakage noise reduction. A 20% wider stall margin is the result of the proportional distribution of the aerodynamic parameters over the rotor.

4.4 Surge and rotating stall

Several sessions were devoted to the topic of surge and rotating stall. The most interesting papers are included in this report. In [19] a rotating stall detection method is presented, based on monitoring of the travelling wave energy and the phase angle of spatial Fourier coefficients. The experimental evaluation of several centrifugal compressor stabilization techniques is discussed in [20]. Although all methods result in lower compressor performance the results showed that tangent air injection, reverse tangent air injection, and vaneless space bleed tubes all improve the stable operating range. Some other papers will be highlighted briefly now. In [21] the results are discussed of experimental investigations on a centrifugal compressor using LDA. The paper discusses the used measurement and data reduction methods. Finally, some conclusions are drawn from the various interesting observations. The obtained results reveal the clear relations between surge and rotating stall.

In [22, 23, 24] numerous experimental results are presented of experiments on a high pressure centrifugal compressor. In collaboration with Nuovo Pignone the authors varied the geometry of different compressor elements and investigated their influence on rotating stall inception. The results are of particular relevance for compressor designers, but the experimental approach provided some useful insights and new ideas for my research.

The number and speed of stall cells is discussed in [25]. The paper mainly focusses on how to define a stall cell and its speed. Based on the pressure distribution in the circumference of a specific transverse cross-section at a specific time the stall cells are counted and their speed is investigated. Although the number of cells can vary in different transverse cross-section of a multistage compressor, the authors conclude that the pressure field rotational speeds and accordingly the rotation speeds of all stall cells appear to be the same.

4.5 Unsteady flow

Finally, two other papers on unsteady flow appeared to be interesting. In [26] a calibration approach is presented for unsteady flow measurements with a Kulite pressure transducer. After taking effects of temperature drift into account, the sensor output is compared with other measurements. Although the results look promising, this paper again proofs that unsteady flow measurements are difficult to perform in practice.

The modelling of unsteady and non-linear flow in a complex piping system is discussed in [27]. The presented approach and findings are very similar to those that can be obtained with the PULSIM simulation tool of TNO TPD. The paper provided some insight for TNO into the efforts of competitors (Siemens) in this field, but it did not provide any significant new ideas or results.

5 Conclusions

At the ACC there were several topics that received a lot of attention and that look promising for scientific developments in the (near) future. First of all, a lot of papers dealt with nonlinear systems in one way or the other. Remarkable is that in many of these papers, links were sought with linear systems and control theory to tackle the specific nonlinear problems. Closely related to the general class of nonlinear systems, hybrid systems were discussed extensively during the conference. Another key topic was in my opinion fault detection. Although many papers still only treated model-based detection and identification schemes, the large number of theoretical papers in this area indicate that progress is made. Therefore I think that extensions and significant improvements in this area are to be expected soon.

Due to the large scale of the Turbo Expo it is hard to tell which topics were of special interest during this conference. The topic of fault detection and engine diagnostics received quit some attention. The goals of most of this research however was fairly conservative. It mainly focusses on keeping the equipment from braking down and being able to respond to malfunctions in an early stage. The application of CFD to model flow phenomena in turbo machinery (components) also got a lot of attention and some interesting results were reported. However, due to the complexity of these techniques and the large uncertainties that still remain, it seems wise to treat CFD with caution.

Surprisingly the topic of unstable flows in turbo machinery did not received that much attention. There were only a few sessions on unstable phenomena like surge and rotating stall. Many of the papers in those sessions presented experimental results for component or small-scale installations. The main focus of most of these papers was on rotating stall. In my opinion, the relationship and the differences between surge and rotating stall did not receive enough attention during the conference. Finally, I noticed that only a few papers were the result of a real collaboration between science and industrial practice. Given the large scope of the conference this was remarkable, although the apparent conservatism of the turbo machinery industry could explain this low level of collaboration with scientists.

The visit to the GTL provided me with some useful contacts at the MIT. The biggest strength of the GTL is their expertise with physical modelling of turbo machinery and the contacts they have with the aerospace industry. Although their current activities are not completely focussed on rotating stall control (and even less on surge control) any more, they still have a lot of expertise in this field. Their enthusiasm about our 'Control of compressor surge with rotating stall' research and their will to assist when possible, could be of value for our project.

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