Project description:

Operation of chemical plants in unstable operating regions

1 Introduction

The background for this project is the realization that the concept of feedback control is underused in chemical engineering (and in most other sciences). Typically, by applying feedback it is possible to widen the range of operation into a region which is more economically attractive.

Most engineers, including chemical engineers, are trained in understanding the basic physics of the problem. This may be done by formulating a mathematical model, and analyzing it, e.g. by performing a sensitivity analysis of its steady-state behavior or performing dynamic simulations. In some cases a more detailed analysis is performed, e.g. in terms of a bifurcation analysis (a special case of which is a a stability diagram for two-phase flow).

However, all this is usually done under the assumption that there is no feedback. This is because most engineers are "feed-forward thinkers" and do not really understand (or believe) that the underlying physical behavior may be affected by feedback.

To give an example, consider some undesired unstable behavior which we want to avoid (stabilize). This could, for example, be slug flow in a pipe line. The intuition of most engineers would then be to model this as carefully as possible, try to identify the location of the slug, and then try to handle the slug in an optimal manner when it reaches the outlet. This is feedforward thinking. However, anyone with a background in control, knows that unstable systems can be stabilized by use of feedback (and only by the use of feedback), e.g by adjusting some valve to avoid that the slug forms in the first place.

The skepticism towards using feedback control to change the dynamics of a system is thus widespread. For example, the classical works of Aris and Amundsen for the 1950's where they proposed to stabilize chemical reactors, were initially dismissed as either wrong or of theoretical interest only. Even though this is today standard text book material, it is nevertheless still not fully understood or accepted, something we have experienced from comments to our recent publication (Morud and Skogestad, 1998) on the stabilization of ammonia reactors.

We plan to start with an extension of the work by Morud and then extend the active use of feedback control to other nonlinear processes, such as compressors, distillation and pipe flow.

The topics and applications presented below are too wide for a single Ph.D. project. The proposed project is therefore planned as the first project in this new area, which we believe is very exciting and has almost endless possibilities for new theoretical and practical results.

Aim

The aim of this project is to study the use of feedback control on stabilizing unstable operating regions. This may be used to widen the existing operating regions or even to discover new ways of operation. We also want to find a tool for identifying how the system may be stabilized. It is believed that the research may open up for further work (e.g. we may be able to stabilize laminar pipe flow over a much larger region that is normally believed possible).

2 Previous work and some issues

There is a very large body of general work on analysis of nonlinear system dynamics and bifurcation analysis (e.g. see Seydel (1988)), and a lot of work has been applied to chemical reaction systems, but this work is of somewhat limited interest where the objective is to avoid this behavior by stabilizing these operating points.

In addition, there is a large body of *general* work on stabilization. For example, it is well-known that any linear system can be stabilized by feedback control provided the unstable states are both observable from the outputs (measurements) and controllable from the inputs (manipulated variables) (The system is then said to be detectable and stabilizable).

However, this work is also of somewhat limited relevance, since there is a long way from even accepting this theoretical result to actually applying feedback control for stabilization in practice.

First, there is the issue of "how fast" the instability is compared to the available measurements and manipulations. This may be quantified by computing the eigenvalue (pole p) of the instability and comparing it with the effective delay θ around the feedback loop. Obviously, a system that goes unstable "too fast" is impossible to stabilize, and for a scalar system we must approximately require $\theta < 1/|p|$ (e.g. see Skogestad and Postlethwaite (1996)).

Second, there is the issue of "how observable" and "how controllable" the states are. We have worked on this recently, and have proved that the concept of *pole vectors* (Havre and Skogestad, 1998a) gives quantitative information about the magnitude of the inputs needed for stabilization and the allowed magnitude of the measurement noise. In short, we want to stabilize the system by using as little input power as possible, and at the same time by allowing the presence of measurement noise and disturbances. The pole vector identifies the best input (valve) and output (measurement) which achieves this.

Third, it is often difficult to understand from a "feedforward thinking" ("open-loop") point of view what the controller is attempting to do during stabilization, and this makes it difficult for engineers and operators to accept implementing a stabilizing controller (e.g. based on simulation results). It may be shown (e.g. Havre and Skogestad, 1998b) that the transfer function from setpoint to inputs has an inverse response when the plant is unstable. For example, if we are controlling a chemical reactor in an unstable operating point and want to decrease the reactor temperature; then we must initially increase the cooling, but eventually as the system reaches its new steady-state the colling will actually be decreased. The reason is that the heat generated by the reaction has decreased, but nevertheless such behavior is counterintuitive and very often leads to the conclusion that the model must be wrong and the controller is not implemented in practice. A similar example is found for unstable distillation columns (Jacobsen and Skogestad, 1995). A third example, is when we are riding a bike and want to user our upper body to tilt the bike to the left (the bike is *not turning*; by tilt we mean that the body of the bike is leaning over). We must then first tilt our body to the left to start the movement, but eventually, at the new steady-state, the body must be tilted to the right to counteract the "off-balance" of the bike.

Fourth, we may not know about the existence of a desirable unstable steady-state. The large body of theoretical bifurcation analysis work may prove to be useful here, but a problem is that models are often very simplified. For example, consider the operation of two-phase flow in new desirable operating regimes. However, if this desirable region is unstable, then it may not have been observed yet, and it is difficult to predict because the models are based on correlations based on observations.

We have also studied the closed operation of multivessel batch distillation (Skogestad et al., 1997) where our contribution was to propose a feedback strategy for operating the column. The column reaches a steady-state at infinite times, but this state is unstable because of the levels.

Again, we found that all previous strategies were based on feedforward thinking ("use the liquid flows to set the level at its precomputed value") whereas many people have had problems accepting our feedback policy ("use the reflux flow to control column temperature and let this indirectly adjust the levels").

Another important application of feedback control for stabilization is in batch distillation and for batch reactors, where "parametric sensitivity" is an issue if we operate without feedback control.

We have here mostly reviewed our own own work. There are of course other people who have worked on use of feedback for stabilization of chemical systems, especially of chemical reactors, but it is surprisingly limited. Some of the these works are mentioned in the above references, and in any case the first part of the Ph.D. project will be devoted towards making a survey of existing literature on "Operation of chemical plants in unstable operating points".

3 Case studies

We here list some case studies we plan to consider.

3.1 Extension of ammonia reactor case study

The goal of this case study is to finish up some earlier work and to give the Ph.D. candidate a good introduction into the use of feedback control for operation in unstable operating regimes.

The starting point will be a ammonia reactor case study based on a Norsk Hydro reactor which was studied in the group a few years ago (Morud and Skogestad, 1998). In that paper it was shown that the reactor may become unstable in some cases, and it was claimed that the reactor may easily be stabilized by feedback control. However, this was not actually demonstrated, mainly because the authors thought it was rather obvious. However, later other authors (Manscuni. Merola, Maffettone and Crescetelli, to be published in *AIChE J.* in 2000) claim that stabilization is not possible, or at least difficult. We therefore want to perform a more detailed study to prove that stabilization of the reactor is indeed feasible, and we will study the robustness of the feedback control.

3.2 Other chemical reactors

We next plan to focus on the stabilization by feedback of some other other chemical reactors, and make use of the extensive literature on bifurcation analysis for unstable reactors. The aim is to study interesting industrial systems where operation in to open-loop unstable operating point is desirable.

3.3 Surge control

Another case study is planned to be compressor control, where it is well known that one cannot operate at the optimal point because one needs to stay away from "surge". Here, "surge" is just another name for a flow-pressure instability, and we believe that we with feedback may operate inside the surge region. There has been some previous work in this area, e.g. see Ecker and Nett (1993).

3.4 Fluidization

To maintain the stability of the fluidized state, it is common to operate the unit (reactor) at higher gas velocities than is necessary to achieve fluidization. By use of feedback control, it may be possible to operate closer to the stability border and thus get more economic operation.

3.5 Stabilization of desired flow regimes

This is an area of enormous potential, where little work has been done. One familiar example would be to stabilize pipe laminar flow above Re-numbers of 2300, but this is probably unrealistic in practice, at least in the near future, because the time and length scales are quite short.

However, there are some cases, in particular related to two-phase flow, where the time constants are much slower, and where stabilization may be feasible. For two-phase pipe flow one distinguishes between various flow regimes, e.g. the enclosed Baker diagram, and uses a separate correlation for each region. The Baker diagrams are essentially showing the stability regions for various flow regimes (e.g. see Brill and Beggs, 1979). By using feedback control it should be possible to enlarge the possible region of operation of a desired flow regimes, for example, to have stratified flow in a region where one would with no control have slug flow. If this is possible, it would represent a fundamental breakthrough with very large potential for practical use.

Indeed, some results full-scale test by Kjetil Havre at ABB (received his Ph.D. with Skogestad as a supervisor in 1998), show that, in spite of what most of the experts claimed, it is possible to stabilize terrain induced slug flow. This is done by measuring pressure (output) and adjusting some appropriate valve (input). Terrain induced slug is probably relatively easy to stabilize because of the long time constants, but it is a very important problem in itself which deserved further theoretical studies, and it shows the potential of using active feedback control.

Another interesting issue is the fact that there may be desirable unstable flow regimes, which have not been observed yet. This follows since turbulent flow in general, and turbulent two-phase flow in particular, is almost impossible to simulate based on the fundamental equations (mostly because the computers are not powerful enough), and one has to rely on correlations. However, up to now these correlations are based on observations for cases with no active use of feedback control. Thus, it will be necessary to enlarge the region of validity of the presently used model.

One should note that the important point is to have a good model of the desirable unstable flow region, and *not* of the stable undesired flow region. For example, if one wants to achieve laminar instead of turbulent flow, then it is of little interest to model the turbulent flow region in detail. Rather, one wants to model the laminar flow region, and obtain information about its rate of instability (location of unstable eigenvalue/pole) and how easy it is to observe and affect (unstable pole vectors). Note here that the beginning instability of laminar flow is quite long-range and with long time constants, compared to the length and time scales of the fully developed turbulent flow In other words, turbulent flow is the chaotic state which starts with the "long-range" instability of laminar flow, and it is this long-range instability which one needs to understand and stabilize. Since these beginning instabilities are small in magnitude, a linear analysis may yield invaluable information.

Obviously, it will not be able to study all these issues in a single Ph.D. project, so it is expected that this more basic project will be the basis for a number of other more specific projects.

4 Cooperation

We foresee an extensive national and international cooperation on this project. We have already close contacts with some strong groups, and we are members of two European networks focusing on the control of complex systems; the EU-supported CAPE.NET project and the ESF-funded COSY project.

We expect to have at least one additional Ph.D. student starting on a project related to the stabilization of two-phase flow, and we plan to have close cooperation nationally (within the university and with industry) on this activity.

It is planned that the Ph.D. student should spend at least 6 months in residence at a recognized foreign institution.

5 Summary

By considering several important examples, our aim is to build up a framework for stabilizing nonlinear chemical processes in new operating points. Since the beginning instabilities are small in magnitude, we will make use of linear system theory, e.g. the concepts of eigenvalues/poles and pole vectors, and apply these to the above examples. To identify possible new operating points, we may make use of results from bifurcation analysis. We foresee that this project may lead to a number of interesting future projects, many of them with significant scientific and industrial and potential.

Enclosed

1. Typical two-phase flow stability diagram (Baker diagram)
2. Pole vector paper by Havre and Skogestad (1998a) (first page)
3. Performance limitations paper by Havre and Skogestad (1998b) (first page)
4. Ammonia paper by Morud and Skogestad (1998)(first page)
5. Distillation instability paper by Jacobsen and Skogestad (1995) (first page)

References

[1] J.P. Brill and H.D. Beggs, 1979, *Two-phase flow in pipes*, Third Edition.

[2] Eveker, K.M. and Nett, C.N., 1993. "Control of Compression System Surge and Rotating Stall: A laboratory-Based 'Hands-On' Introduction", Presentation at *1993 American Control Conference*

[3] E.W Jacobsen and S. Skogestad, 1995, "Multiple steady-states and instability in distillation - implications for operation and control", *Ind.Eng.Chem.Res.*, vol. 34, 4395-4405.

[4] K. Havre and S. Skogestad, 1998a, "Selection of variables for regulatory control using pole vectors", *Proc. IFAC symposium DYCOPS-5*, Corfu, Greece, 08-10 June 1998, 614-619

[5] K. Havre and S. Skogestad, 1998b, "Performance limitations for unstable SISO plants", *Proceedings 1998 American Control Conference*, Philadelphia, USA, 24-26 June 1998, 3234-3238

[6] J. Morud and S. Skogestad, 1998, "Analysis of instability in industrial ammonia reactors", *AIChE J.*, vol. 44, pp. 888-895.

[7] R. Seydel, 1988, *From equilibrium to chaos: practical bifurcation and stability*, Elsevier

[8] S. Skogestad, B. Wittgens, R. Litto and E. Srensen, 1997, "Multivessel batch distillation", *AIChE J.*, vol.43, pp. 971-978.

[9] S. Skogestad and I. Postlethwaite, 1996, *Multivariable feedback control*, Wiley.