Abstract

For a controls experiment to be meaningful, it should provide knowledge that cannot be gained from theory or simulation. The authors maintain that the value of experiments is proportional to their fidelity to an industrial motivating problem. Without this, claims regarding the efficacy of a control method cannot be substantiated to any degree more than they could via simulation. The control of a high speed milling spindle is reviewed as an example of a problem where only a prototype experiment is compelling.

1 Introduction

From the authors' experience, industry often perceives that academic efforts in automatic control have little relevance to 'real world' problems. Control experiments may help in narrowing both the real and perceived gaps between industrial practice and academic research. However, for experiments to achieve this objective, the role of control experiments needs to be carefully considered. We will do so herein drawing on our extensive experience with the control of active magnetic bearing systems.

A controls experiment seeks to examine if theory produces an adequate solution to a particular problem. For this to be meaningful, the experiment should establish a result that cannot be practically determined purely from theory or simulation. Herein, meaningful refers to the contribution of the experiment to the development of control technology. Experiments that have only pedagogical value are not examined. It is important to point out that, with increasing computational capability, the academic researcher can now conduct very complex simulations that only a decade ago would have been impractical. Given this, why still do experiments? What can they contribute?

2 The Standard Answer

The standard answers to these questions emphasize the inaccuracy of theoretical and simulation models. Mathematical models have the unfortunate effect of continually inspiring greater confidence in them than is warranted. Often, the degree of modeling error (or parameter variation) examined in theoretical or simulation studies is insufficient in comparison to that actually present. Also, important phenomena may simply be missed in the construction of a model. Even when considered, many phenomena present in physical systems (such as internal damping in flexible rotors) are very difficult to accurately model in simulation or incorporate into a theoretical framework. Also, models of exogenous signals (especially sensor noise) may be difficult to obtain since their characteristics may be time varying or correlated with the state or control signal (e.g., noise induced in an inductive sensor by stray field from a nearby magnetic bearing).

In principle, both physical phenomena and exogenous signals could be incorporated into a highly sophisticated simulation. However, validating the modeling techniques used may require building and testing an experiment. Indeed, the effort and cost required to construct and validate the simulation may be similar to that required for experimental investigation.

In summary, the standard viewpoint states that hardware experiments are compelling due to a lack of confidence in the simulation model. But this is only a partial answer to the question.

3 Importance of Industrially Motivated Experiments

As outlined above, an experiment may examine the significance of the simplifying assumptions which lead to a tractable analysis or synthesis framework. However, the experiment is usually only a representation of the motivating industrial application’s hardware, disturbances, and performance requirements. Can this representation be validated as well? This is considerably more difficult question for the academic experimentalist, but perhaps no less important.

A well designed controls experiment should retain sufficient fidelity to industrially realizable equipment to provide a convincing indication that the theory is truly
applicable to the motivating problem. The importance of this becomes clearer if we examine in more detail what makes an experiment meaningful.

A meaningful controls experiment is one that determines whether theory is practical for an industrial application; specifically, it determines if theory yields a controller that can operate adequately with:

- typical measurements (number of sensors, noise levels, drift, bandwidth, and nonlinearity).
- available actuators (type, number, bandwidth, linearity, hysteresis, and deadzones)
- reasonable control authority
- typical levels of model uncertainty
- available controller hardware.
- acceptable levels of size and complexity

Note that theory or simulation may also be able to address many of the above issues. However, with theory or simulation, the qualifiers typical, reasonable, and available have a much greater degree of flexibility than in an experiment. The meaning of each of these qualifiers, of course, can only be appropriately determined in the context of the industrial problem examined. Control experiments may be (often are?) designed such that this meaning is lost in the translation from the industrial problem to the experimental problem. For example, sensors may be included at locations in the experiment that are not practical in the industrial application. Or actuators may be given significantly greater authority than is industrially practical. Often, experiments are designed that are not representative of any industrial application (e.g., the inverse pendulum). While these may have tremendous pedagogical value, they may not be meaningful (i.e., since the results could be established by simulation alone).

Experimental results cannot be used to directly evaluate the fidelity with which the experiment represents the motivating industrial application. Working with experiments, however, may have a subtle and beneficial effect in this regard. During the design, construction, calibration, and identification phases of the controls experiment, the experimenter gains very valuable insight into the industrial application and how the experimental hardware represents it. This knowledge helps to narrow the gap between this representation and reality. The meaning of the qualifiers typical, reasonable, and available may solidify through the experimental process.

The academic researcher is not a disinterested party in the development and application of control theory. While not intentionally ignoring important issues, the researcher will have a natural tendency to discount inconvenient hardware realities. The flexibility of theory and simulation permits the researcher to do so without any repercussions. The researcher may claim that the effects that were ignored (e.g., hysteresis) were not important or those included (e.g., modal damping) are achievable. But without experimental experience, on what are these claims based? Furthermore, if these claims are based upon experience with non-representative experiments, can they be trusted?

It is tempting for the researcher to claim that, if “good” hardware were designed, the assumptions of the control theory would be valid. Here, the difficult problem (e.g., control of hysteretic actuators) is being passed off to industry rather than being addressed by the control engineer. The application of automatic control should remove constraints upon hardware, not impose them. Meaningful control experiments force the researcher to tackle these challenges since they focus on realistic and relevant problems. This directs theoretical efforts to many of this field’s most interesting problems. This beneficial effect can only be guaranteed if the experiment is representative of an industrial system.

4 A Straw Man

Consider the following fanciful scenario: In an effort to boost experimental controls efforts, a government agency grants all academic controls researchers an inverted pendulum experimental kit. Soon, research centers nationwide are intensely scrutinizing the dynamics of inverted pendulums. Nonlinear controllers are designed. Neural networks are trained. And adaptive controllers are proven to yield global asymptotic stability.

Sophisticated research teams soon construct their own double inverted pendulums and devise advanced methods for eliminating troublesome joint friction. In testing of a triple inverted pendulum system, a prestigious university discovers that the joint friction cannot be made sufficiently small so as to be ignored in designing controllers. Its best minds then focus on the development of variable structure controllers for the triple inverted pendulum problem with joint friction. Special properties of the structure of the nonlinearities of multi-inverted pendulum systems are exploited in devising Lyapunov functions. Soon, the National Center of Excellence for the Control of Multi-Inverted Pendulums has been established with government support. Eighteen months later, a text on the subject appears.

The point of this tongue-in-cheek story is simple: control researchers can apply tremendous sophistication to meaningless problems. Performing experiments does not protect them from doing so. While some practical knowledge may result from such efforts, the fruit of this aloofness will be a justifiably poor relationship with industry.

How closely does an experiment need to represent industrial hardware? Is it necessary for researchers to conduct experiments on machine prototypes?

5 A High Speed Milling Spindle

These questions will be partially examined here by reviewing an ongoing project where prototype testing is the only compelling experiment: the control of cutting-induced chatter on a high speed milling spindle using active magnetic bearings.
Active magnetic bearings (AMB) have several advantages over conventional rolling element bearings for high speed machining. Magnetic bearing spindles have greater stiffness and a longer life than a conventional spindle. Also, the active nature of magnetic bearings can be exploited to achieve much lower vibration levels than obtainable with rolling element bearings. One particularly interesting advantage of magnetic bearings is the ability to actively suppress machining chatter.

Chatter is a self-excited vibration that occurs in machining. It is caused by the interaction of the cutting process with the dynamics of the spindle and machine tool. These two stable systems form a closed loop which may be unstable. The amplitude of this instability is limited by the cutter teeth jumping out of contact with the workpiece. Chatter vibration degrades the finish of the machined part and reduces the life of the cutting tool. It ultimately restricts the achievable metal removal rate.

5.1 Control Goals

The cutting force acting on the tool depends upon many factors which are specific to the machine tool and type of cut (e.g., slotting, face milling, end milling). Description of such factors is beyond the scope of this paper. The cutting force will be predominantly composed of harmonics of the cutter tooth-pass frequency (forced vibration) and perhaps a machining chatter frequency (self excited vibration). The controller design goals are to (i) reduce the tool harmonic response at multiples of the tooth-pass frequency and, (ii) suppress the onset of machining chatter. The first of these goals may be accomplished by minimizing the $H\infty$ norm of the cutting tool dynamic compliance since the spindle speed and number of cutter teeth varies.

Chatter can be characterized by a maximum width of cut which yields stable machining under all conditions. This maximum cut width is given as [1]:

$$b = \frac{1}{2K_r \text{Re}[G]}$$

(1)

where $K_r$ is the cutting stiffness of the workpiece material and $\text{Re}[G]$ is the real part of the oriented transfer function of the tool. In the absence of a specific cutting process, chatter may be assumed to occur at the most negative real part of the dynamic compliance of the cutting tool. Therefore, in order to achieve the highest metal removal rate without chatter, the minimum real tip compliance of the spindle should be maximized by the control design. This goal, too, may be cast as an $H\infty$ specification through the use of a linear fractional transform [2].

Plant uncertainties must be included in the design procedure since the rotor is very lightly damped. Fortunately, the uncertainties in this system are highly structured (often parametric). In principle, controllers may be designed which sacrifice only a little performance to achieve the necessary robustness.

5.2 UVa Spindle

To investigate these control issues, the authors have been developing a new high speed machining spindle controlled by active magnetic bearings. This spindle has recently been magnetically levitated via feedback control and is undergoing preliminary testing.

Figure 1 shows a schematic of the AMB milling spindle with three radial magnetic bearings, termed the nose, mid-span, and tail bearings. The shaft is dual level with a large rotor on which all bearing journals and the motor rotor are carried, and a smaller drawbar located within an internal bore of the main rotor. The purpose of the drawbar is to hold the cutting tool during machining yet allow it to be released, allowing the tool to be changed. Four flexible modes of the lightly damped rotor-drawbar are within the target controller bandwidth of 2 KHz. A photograph of the spindle is shown in Figure 2.

The spindle uses differential optical sensors to determine the radial and axial position of the shaft. Optical sensors have the advantage of being immune to magnetic fields and therefore have very low noise. This is an important characteristic for the high gain feedback control which the bearings will use. The sensors, designed at University of Virginia, are based on occlusion of a light beam from an infrared LED to a phototransistor by the shaft.

The magnetic bearing spindle uses a parallel processing digital controller designed and built at the University of Virginia [3]. Four Texas Instruments TMS320C40 digital signal processors are used for control algorithm computations. Controller throughput will depend on algorithm execution times; preliminary testing indicates a throughput rate in excess of 10 KHz.

5.3 What We Will Learn

The design, fabrication, and assembly of the experiment has already provided us with a great deal of insight into issues regarding noise, control authority, and bandwidth. We expect that our future experiments will also teach us important practical lessons regarding modeling and the proper representation of uncertainties for these systems. Furthermore, an evaluation of cutting performance and its correlation to the figures of merit used in synthesis can only be accomplished via cutting experiments.

For the spindle under consideration, a planar, dual level rotordynamic model of the rotor and drawbar may be used since the gyroscopic effects are negligible. Significant uncertainties occur in the modeling of the spindle rotodynamics because different cutting tools will be used. This results in a 15% variation in the first flexible-mode natural frequency of the rotor. Our theoretical results indicate that a controller that is designed to be robust to such a large variation in cutter mass will have very poor performance. However, this measure of performance is itself artificial. One important question is whether the actual cutting performance of such a robust controller will indeed be so poor as to justify a gain scheduled control approach. If it is not, optimization
cost functions which more accurately capture the important aspects of cutting performance will need investigation.

In addition to the tool mass variation, the complex drawbar employed may provide a considerable challenge in developing a good nominal model and uncertainty representation. The actual contribution of the drawbar to the system dynamics is still unknown at this time. Only experimental testing will help us in clarify these modeling and uncertainty representation issues.

The magnetic bearings of the spindle will be operating at very high surface speeds. Eddy currents will be generated in the laminated journal due to the changing magnetic field with rotation. Earlier experiments with lower surface speed bearings have not indicated any speed dependence of the actuators’ transfer functions due to these effects. This assumption is incorporated into our synthesis model. Once again, only experimental testing will indicate whether this problem formulation is sufficiently accurate.

How will the knowledge gained affect the way we practice control theory? It is difficult to answer this question at this time since the experimental outcome is unknown. But, what we have learned from our previous experimental experience with industrial applications might give some idea about what we might learn from this effort. Previous experience has taught us:

- the importance of model-based identification and structured uncertainty representations to obtaining good performance.
- the significance of small dissipative effects as well as actuator slew rate limits in preventing and limiting high frequency spillover instabilities for controllers with reasonable bandwidths.

The first of these has lead us to carefully consider our testing procedures for identification. It has also reinforced the importance of a good algorithm for synthesis of controllers for plants with real parametric as well as dynamic uncertainties. As a consequence, some research is now being done in these areas. The second point has inspired a great deal of discussion but not any research efforts as of yet. However, it will become increasingly important as we move toward controllers with higher authority and bandwidth.

6 Conclusions

For an experiment to be meaningful, it should provide knowledge which cannot be gained from either theory or simulation. Today, the simulation of very complex dynamical systems is practical. In the light of this ever increasing
capability, the role of control experiments needs to be re-examined.

We posit that experiments are meaningful in proportion to their representation of industrial problems. This conclusion derives from the fact that the applicability of control theory to actual problems can only be evaluated in terms of qualifiers such as “typical” and “reasonable”. The proper meaning of such terms can only be determined from experience with representative hardware.

If an experiment is not representative of the industrial motivating problem, there is little basis upon which to evaluate claims regarding the merits of any control approach. The critical connection that justifies conducting an experiment rather than a simulation has been broken. Only the pedagogical value of a working control system remains.

Industrially representative control experiments educate the researcher in the feasibility of actuation, sensing, and modeling. They emphasize the restrictions that hardware imposes upon control design rather than those that the control design imposes upon the hardware. They direct research efforts to many important theoretical problems. Experiments that are not representative of industrial problems are unlikely to provide these benefits.

The degree to which experiments are required to represent the industrial motivating problem is, of course, problem dependent. For some control problems, such as the AMB milling spindle discussed here, only an experimental prototype is fully satisfactory. For others, much simpler experiments may suffice.

References

