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CONTROLLING FLEXIBLE STRUCTURES - A SURVEY OF METHODS

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ABSTRACT

Most of the presently available control system design techniques applicable to flexible structure problems were developed to design controllers for rigid body systems. Although many of these design methods can be applied to flexible dynamics problems, recently developed techniques may be more suitable for flexible structure controller design. The purpose of this presentation is to examine briefly the peculiarities of the dynamics of flexible structures and to stimulate discussion about top level controller design approaches when designing controllers for flexible structures.

This presentation contains a suggestion of a set of categories of design methods for designing controllers for flexible structures as well as a discussion of the advantages and disadvantages of each category. No attempt has been made herein to select one category of design techniques as the best for flexible structure controller design. Instead, it is hoped that the structure suggested by these categories will facilitate further discussion on the merrits of particular methods that will eventually point to those design techniques suitable for further development.

CHARACTERISTICS OF FLEXIBLE STRUCTURE DYNAMICS

Flexible structure dynamics tend to differ from rigid body dynamics in several important ways. First, flexible dynamics are higher order than rigid body dynamics. By definition, rigid body dynamics involve six degrees of freedom. Since each degree of freedom results in two states, the full set of dynamics for a rigid body system will involve only twelve states. (Additionally, servo, actuator, sensor, and controller compensation states must be added.) By comparison, a flexible structure model may have 100 or more states. This increase in the number of states derives an increase in the complexity of the control problem. Hence, those design techniques which work well for tenth order systems may have difficulties handling systems with ten times that many states.

A second important difference between rigid body and flexible dynamics is flexible dynamics tend to be more difficult to predict than rigid body dynamics. It is the structure of a system which derives its flexible dynamics. Parameters such as mass distribution, material stiffness and damping, and unsteady aerodynamics become influential. Often mathematical models developed to predict the flexible dynamics differ with the physical system representation. As a result, the controller design based on these prediction models must be made robust to withstand the discrepancies between the model and physical system.

A third difference between these dynamics is that rigid body dynamics can often be treated as decoupled, whereas flexible body dynamics are most often highly coupled. As a result, control problems that can often be treated as a single input / single output (SISO) or as a series of SISO problems when dealing with rigid body systems, become multiple input / multiple output (MIMO) problems when dealing with flexible systems. SISO methods appropriate for decoupled rigid body system controller design may be unsuitable for flexible system controller design.

A fourth difference between these dynamics is the goal of the systems designed to control them. Rigid body control usually involves commanding the rigid degrees of freedom to follow desired trajectories. For an airplane these might be altitude, heading, and airspeed. By contrast, the goal of most flexible structure controllers is either to perform the desired rigid body control without exciting flexible modes, or to provide active damping for structural modes that are excited. In almost all applications the objective is to keep flexible structure dynamic responses at the lowest possible levels. The difference between the goals for rigid body control and flexible structure control may require different controller design approachs.

CONTROLLER DESIGN METHOD CATEGORIES

Four categories of controllers are detailed in the following paragraphs with a discussion on the advantages and disadvantages of each category with respect to the design of controllers for flexible structure systems. It is not the author's intent to favor any category of controller design techniques over another. The divisions herein are made simply to facilitate comparison of different top level strategies for the design of controllers for flexible structures. The categories are deliniated by the types of models each use for controller synthesis, and whether the controller is designed off-line, on-line, or both.

1) Off-line Modeling / Off-line Controller Design

Off-line modeling / off-line controller design techniques have been historically used as the standard for control system design. This technique consists of building up a model using mathematical prediction, wind tunnel analysis, and flight test data. Controllers are then designed off-line based on the model. Although separate controllers may be designed for different flight conditions (i.e., requiring gain scheduling based on flight condition), only these on-line modifications defined previous to flight are made to the controller.

This category of controller design techniques has the advantage of all controller synthesis work being completed ahead of time off-line. As a result, the on-line computational load is kept to a minimum. In addition, since the controller is well defined for each flight condition, rigorous analysis is possible for predicting performance and robustness characteristics.

A disadvantage of this controller design approach is that discrepancies between the model and the physical system itself must be handled solely by controller robustness. The controller is unable to tune itself to account for modeling errors or changes in the dynamics as a result of different flight conditions or weight distributions. Hence, this design approach requires development of an accurate system model. Whenever possible, the off-line model is updated to concur with the obtained test data using the physical system to be controlled. In those cases where test data is not available, analysis must be done to show that the controller will function in an acceptable manner for the set of anticipated dicrepancies between the model and the physical system.

2) Off-line Modeling / On-line Controller Design

The same type of model used for the previous category of controller is used for off-line modeling / on-line controller design techniques. However, the primary difference with this category is that while the controller structure is defined off-line, the controller gains are adapted on-line to minimize certain performance criteria. With this technique no attempt is made to model the open-loop system on-line, and all controller gain changes are made solely in response to performance criteria.

This approach has the advantage of the controller being able to tune itself to account for parameter variations between the model and the physical system. The off-line system model does not have to be as precise for this type of controller as for those described in category 1. The off-line model is used to note the structure of the system and the general trend of the dynamics. Furthermore, a related advantage is that since the controller is able to tune itself, gain scheduling does not have to be as detailed as for a controller that is designed completely off-line.

A disadvantage of this approach is that the controller must be tuned on-line, thus requiring more computation power. Another disadvantage is that while the controller is able to tune itself to account for parameter variations, its structure is fixed. If the structure of the flexible system changes or there are wide swings in its general dynamics, the controller may not be able to tune itself sufficiently to provide the necessary control. A third disadvantage is that while the controller is continuously tuning itself, it is impossible to predict the gains for any given flight condition. As a result, it is impossible to obtain the level of performance and robustness analysis possible with each flight condition assigned a fixed set of controller gains.

3) On-line Modeling / Off-line Design

On-line modeling / off-line design techniques define the controller in terms of a general open-loop system model of a specified structure. With these techniques each controller gain is defined as a function of model parameter values. Implementation consists of building an on-line adaptive estimator to estimate the model parameters. The controller gains are then set based on the model estimate values per the definitions developed off-line.

An advantage of this approach is that the controller gain definitions can be chosen to give the desired performance and robustness properties regardless of the model parameters. (It is assumed that sufficient controllability and observability exist for all variations of the model parameters.) Gain scheduling is not an issue since the controller gain definitions automatically give appropriate gains for any given operating condition.

A disadvantage of this approach is that the controller gains must be defined symbolically rather than numerically. Controller synthesis requires solution of symbolic rather than numeric equations. Fortunately this task is done off-line and will not require real-time computing resources, but it is still a formidable task nonetheless. Another disadvantage is that on line estimation of the model parameters is required along with computation of the controller gains. Evaluation of the equations defining the controller gains may be quite expensive to compute. An additional disadvantage is that the controller gain definitions may include singular points within the region of possible model parameter sets. A method to avoid singularity is needed.

4) Off-line Modeling / Off-line Controller / On-line Adjustment

The final controller design approach category involves off-line modeling, off-line nominal controller design, and on-line controller adjustment. The nominal controller is designed to stabilize the nominal system. With this technique an adaptive loop is placed around the system to tune the control input for improving the off-nominal performance. This adaptive loop is designed to consistantly stabilize the nominal system. Furthermore, when the system is at nominal, the adaptive control signal is zero.

An advantage of this system is that while the controller is able to tune itself to account for modeling errors, the tuning is restricted so that the closed-loop system remains stable. This method can be thought of as a compromise between a fixed gain controller and fully adaptive controller. The nominal controller gains are fixed while the adaptive algorithm is free to vary the gains within a range about nominal.

A disadvantage of this system is that if the physical system varies greatly from the nominal given by the off-line model, there is no longer a guarantee of stability.

Hence on the one hand, the adaptive tuning is restricted to keep from destabilizing the nominal system. On the other hand, this restriction may lead to a situation where the actual system is driven unstable and the limitations on the adaptive tuning are such that the controller is unable to tune itself sufficiently to provide closed-loop stability.

SUMMARY

Rather than point to a single design approach as the best for designing controllers for flexible structures, the goal of this presentation is to simulate thought and discussion. Most likely a single approach is not well suited for all problems. The key is to realize that there are fundemental differences between rigid body and flexible structure dynamics and that these differences may require different approaches to controller design.

CONTROLLING FLEXIBLE STRUCTURES:

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Goal of Presentation:

Stimulate discussion of merits and maturity of different top level approaches to controller design for flexible structures

Outline of Presentation:

- o Characteristics of Flexible Structure Dynamics
- o Four Categories of Controller Design Approaches
- o Open Discussion on Merits and Maturity of Design Approaches

Characteristics of Flexible Structure Dynamics

- o High order (100 or more states)
- o Difficult to predict
- o Coupled dynamics

Four Categories of Controller Design Approaches:

1) Off-line Modeling / Off-line Controller Design

2) Off-line Modeling / On-line Controller Design

3) On-line Modeling / Off-line Design

4) Off-line Modeling / Off-line Controller Design / On-line Adjustment

1) Off-line Modeling / Off-line Controller Design

- o Model developed off-line using mathematical predictions, wind tunnel data, and/or flight test data
- o Controller designed based on model
- o Controller structure and gains may vary from condition to condition but controller is fixed for a given operating point

Advantages:

- o Low on-line computation requirement
- o Well defined controller allows for rigorous analysis

Disadvantages:

- o Controller cannot react to modeling errors
- o Model must match physical system closely
- o Controller must have significant robustness

2) Off-line Modeling / On-line Controller Design

- o Model developed off-line using mathematical predictions, wind tunnel data, and/or flight test data.
- o Controller structure chosen based on off-line model
- o Criteria outputs specified to drive controller adaptation
- o Controller gains adapted on-line in effort to minimize criteria outputs

Advantages:

- o Controller can tune itself to overcome modeling errors
- o Model must represent structure and general trend of the dynamics, but need not be exact

Disadvantages:

- o On-line gain tuning requires greater computational power
- o Gains may diverge resulting in an instability
- o Because gains are not fixed for a given flight condition, rigorous closed loop analysis is not possible

3) On-line Modeling / Off-line Controller Design

- o System model adapted on-line to fit a specified structure
- o Controller gains defined as functions of model parameters
- o Controller gain equations developed off-line as functions of generalized model parameters

Advantages:

- Controller gain equations give explicitly the desired performance and robustness characteristics
- Controller gain equations developed off-line and must be computed only once

Disadvantages:

- Controller gain equations must be solved symbolically rather than numerically
- On-line model estimation is computationally expensive

4) Off-line Modeling / Off-line Controller Design / On-line Controller Adjustment

- o Model developed off-line using mathematical predictions, wind tunnel data, and/or flight test data
- o Controller structure defined based on off-line model
- o Nominal controller gains chosen based on off-line model
- o Controller gains allowed to adapt on line in such a way that the nominal plant (as defined by the model) is never driven unstable

Advantages:

- o Controller can tune itself to adjust to modeling errors
- o Controller self tuning is restricted to maintain stability of nominal plant as defined be the model

Disadvantages:

- o Controller may not be able to tune itself sufficiently
- o Analytical analysis difficult because controller not fixed for a given flight condition

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GUIDANCE AND CONTROL RESEARCH

Discussion of Merits and Maturity of Top Level Approaches to Controller Design for Flexible Structures