A multipurpose benchmark for fault diagnosis and control of ‘Smart’
structures

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The current trend in wind turbines and helicopters is to equip the blades with piezo-electric sensors and actuators for vibration control and fault tolerant control. In aircraft systems it is desirable to have information about possible structural damage of the wing to perform controller reconfiguration. In this extended abstract a multipurpose benchmark is introduced based on a beam structure that is a good first approximation of the vibrational behavior of a rotor blade or a wing. The beam can be used as a benchmark for Linear Parameter Varying (LPV) control and identification, fault detection, fault tolerant control, distributed control, as well as integrations of these various methods. The benchmark will be introduced and we will describe how this benchmark can be used in the different fields of interest.

1 Introduction

Within the Delft Center of Systems and Control a theoretical framework is being developed in the area of LPV systems, fault detection, distributed control and ‘Smart’ structures. In this extended abstract the knowledge about ‘Smart’ structures is used to develop a benchmark with as main goal to combine this with the theoretical framework. A piezoelectric actuated mechanical structure is built on which the different algorithms can be evaluated and further developed. These piezoelectric actuated mechanical structures are systems that can be seen as a subset of the so-called ‘Smart’ structures. These ‘Smart’ structures are structures with highly distributed built-in sensors and actuators that can adaptively sense and actively change their physical geometry and properties under external stimuli. Applications of piezoelectric materials as sensor and actuator in physical structures have received attention for their advantages in fast response, lightweight and large force input. In a number of aerospace applications these ‘Smart’ structures have already played a major role [1]. With relatively new application fields as the wind energy and the automotive industry the focus of the research tends to go to LPV, fault tolerant and distributed control.

In this extended abstract we will first introduce the benchmark in section 2. In section 3 the LPV system approach is introduced. In section 4 the framework of fault tolerant control is introduced. In section 5 the focus is put on distributed control and finally in section 6 we finish this extended abstract with some conclusions and future work.

2 Benchmark

The proposed benchmark is a flexible clamped beam equipped with a number of piezoelectric actuators and sensors distributed over the length of the beam. The piezoelectric patches are used in
the so-called d_{31} configuration to temporarily deform the structure. The dynamics of the clamped beam can be altered by appropriate (time-varying) feedback controllers, F(t). At the end of the beam a force actuator and position sensor is attached. This actuator and sensor are connected to each other by a time-varying feedback controller to form a ‘virtual’ adjustable spring/damper that can be used to simulate time varying dynamics. A schematical view of the proposed benchmark is given in Fig 1.

![Schematical view of the benchmark](image)

Figure 1. Schematical view of the benchmark

For the conditioning, data acquisition and controller implementation additional hardware is required. For the data acquisition and the controller implementation a Dspace™ [2] system is used. Furthermore, high voltage amplifiers are used to steer de piezoelectric actuators. In the next three sections we will explain how this set-up can serve as benchmark for the different research fields.

3 LPV identification and control

The dynamics of many ‘Smart’ structures is linearly dependent on a measurable scheduling vector such that the dynamics can be modeled in the LPV framework. In (1) a mathematical representation of the LPV framework can be found.

\[
\begin{align*}
x(k+1) &= \sum_{i=1}^{\mu(k)} \mu_i(k) (A_i x(k) + B_i u(k)) \\
y(k) &= \sum_{i=1}^{\mu(k)} \mu_i(k) (C_i x(k) + D_i u(k))
\end{align*}
\]

where at every time instant \( k \) the system is a linear combination of the local state space realizations \((A_i, B_i, C_i, D_i)\) and the scheduling variable \( \mu(k) \) determines the validity of each model. For example, the dynamics of a ‘Smart’ rotor of a wind turbine or helicopter depend among others on the azimuth angle and the rotational speed. The control and identification of these LPV systems is a hot topic in current research [3,4]. The dynamics of the benchmark linearly depend on the control settings of the time varying controller and therefore the stiffness and damping of the benchmark can be varied by varying the settings of the time varying controller using the real-time Dspace™ system.
The preferred LPV identification method is based on subspace identification. This method has been chosen for its non-iterative character combined with its capability to deal with multiple input multiple output systems. Exploiting the structure of the data equations has already resulted in some fundamental results [3]. The LPV model structure is also particularly suitable for the design of parameter-varying controllers. In particular, whenever the time-varying parameters in (1) are known (measured or estimated), an optimal affine LPV controller can be designed via a convex LMI optimization for many popular performance indexes (e.g. H2, Hinf). This has the advantage that (a) improves over the performance of a single robust controller, and (b) circumvents the difficulties with the non-convexity of the robust output-feedback design problem for (1).

4 Fault detection, identification and controller reconfiguration

The beam setup can also function as a test bed for fault detection, isolation and controller reconfiguration (FDIR) methods. The relatively large number of (piezo-electric) sensors and actuators results in a significant increase in the analytical redundancy of the system, opening a wide range of possibilities for introduction of different sensor, actuator and component faults. Moreover, by closing the loop between two adjacent piezo-electric elements with a feedback gain $F(t)$, as shown in Fig 1, the local stiffness of the beam can be increased/decreased in a controlled fashion. This allows for non-destructive real-time introduction of certain component faults. In existing similar setups, component faults are introduced by means of switching beams, which cannot be performed on-line. The additional possibility of including a nonlinear behavior to the beam makes the FDIR problem even more challenging.

The preferred FDI solution uses a multiple model framework. This framework has been chosen for its extensive modeling capabilities. Contrary to other FDI methods, it allows modeling of actuator, sensor as well as component faults by means of the common structure (1). The starting point is the selection of a set of vertex model in such a way that the convex hull of the selected models covers all possible models of faults. The advantage of such modeling is that it allows the representation of an infinite set of possible system faults by means of a combination of a small set of vertex models. Faults can be identified by estimating and analyzing the weights in the convex combination of the models. These weights can be estimated by using existing algorithms, see e.g. [5] and [6]. After a fault has been identified, the controller is reconfigured. For controller reconfiguration the methods developed in [7] could be used.

5 Distributed control

For systems with many sensors and actuators, such as e.g. in active flow control and structural acoustical control, decentralized and distributed identification and control methods need to be used in design and real-time controller implementation. Some progress in the development of distributed control and identification methods has been made [8,9,10], however experimental validation of these methods is still lacking. The proposed benchmark, being distributed and having relatively large number of sensors and actuators, enable practical validation of these methods and speeds up the practical application of efficient distributed control and identification.

The method proposed in [8] is a promising approach in distributed control, since the global performance criterion is written as a convex function of the controller parameters. However the
controller design in [8] is based on a distributed model of the system. To accurately determine such a distributed model new identification algorithms need to be developed. In [10] we have proposed an initial contribution to the identification of distributed models from measured input/output data. Simulation results on a beam system have shown that the method proposed in [10] yields efficiently and accurately a distributed model. It is expected that this will also be the case for proposed laboratory benchmark system.

6 Conclusions and future work
In this extended abstract a benchmark is introduced that can be used as a benchmark for LPV control and identification, fault detection, fault tolerant control, distributed control, as well as integrations of these various methods. In this extended abstract we have introduced the benchmark and we described how this benchmark can be used in the different fields of interest. In future work we will test and develop new algorithms based on this set-up and for distributed control it becomes interesting to look at multiplexing control.

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References