Comparison of Control Strategies for Aircraft Bleed-Air Systems

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Abstract: Bleed-air systems in passenger aircraft are often prone to limit cycle oscillations. Tuning of such systems makes additional flight-tests necessary, generating large expenses. In this paper, several control approaches to improve the performance of bleed-air systems are compared. These approaches combine a base-controller with stiction-compensation techniques. The different approaches are implemented, optimized and evaluated using a high-fidelity bleed-air system model, described in the equation-based modelling language Modelica. Results indicate that interaction between different valves should be reduced as much as possible. If a suitable base control approach is chosen, the influence of a superimposed stiction compensation technique seems to be small.

Keywords: Friction, Stiction, Compensation, Limit Cycles, Modelica, Pistons, Modelling, Oscillation, Pneumatic, Valves

1. INTRODUCTION

In modern passenger aircraft, the cabin is pressurized and temperature-controlled by the Environmental Control System (ECS). Hot and dense air is bled from the engine compressor stages. Pressure and temperature are regulated in the bleed-air system. From there, it is cooled and dehumidified in the air conditioning pack before being ducted into the cabin.

Traditionally, the bleed-air system is prone to limit cycle oscillations. It often uses self-regulating pneumatic valves to control the mass flow, with a superimposed electronic control loop. The valve actuators contain a pneumatic piston and cylinder; as oil cannot be used as a lubricant, the resulting dry-friction can lead to poor performance.

The resulting oscillations are hard to predict both by simulations and test beds. Their occurrence is dependent on engine and flight state. Therefore, the actual performance and stability of a certain architecture can only be assessed adequately during flight tests. This slows down the development of new systems and may generate large costs.

In literature there already exists some work about modelling and control of aircraft bleed-air systems. The authors of (Shang and Liu, 2007) and (Hodal and Liu, 2005) developed a control strategy for both air conditioning pack and bleed-air valves. However, the underlying model does not include the non-linear dynamics of the valve actuators. Valve dynamics are modelled as first-order lag instead. Cooper et al. (2013) developed an adaptive controller for bleed-air pressure control, modelling the valves as a combination of first-order lag and hysteresis. Only a single valve is controlled, interaction effects are not a concern. In the patent by Stokes et al. (1983), a LPV-like technique is used to control the surge bleed valve of an auxiliary power unit. The technique is not expanded to the complete bleed-air system or to the main engines.

In preliminary work, the authors developed a high-fidelity model of self-regulating pneumatic valves as well as a system-level-model in the object-oriented equation-based modelling language Modelica, see (Pollok and Casella, 2015) and (Pollok and Casella, forthcoming). Using this model, limit cycle oscillations could be predicted for the first time.

The goal of this work is to implement and evaluate several control approaches for aircraft bleed-air systems. It is structured as follows: In Section 2, the aircraft ECS is illustrated, a Modelica model of a bleed-air system is presented, and an evaluation criterion for the evaluation of control strategies is defined. Next, in Section 3 several control approaches for bleed-air systems are presented. The evaluation strategy is shown in Section 4 and the results are presented and discussed in Section 5. The paper is concluded in Section 6.

2. LIMIT CYCLES IN AIRCRAFT BLEED-AIR SYSTEMS

2.1 System Structure

A conventional ECS architecture is illustrated in Figure 1.

ECSs are structured as follows: Air is bled from one or two compressor stages of the engines. The downstream pressure is regulated by the High Pressure Valve (HPV) and Pressure Reduction Valve (PRV) and ducted through the wing in the direction of the belly fairing. There, it is controlled for mass-flow in the Flow Control Valve (FCV). From there, the air is cooled against outside air, expanded

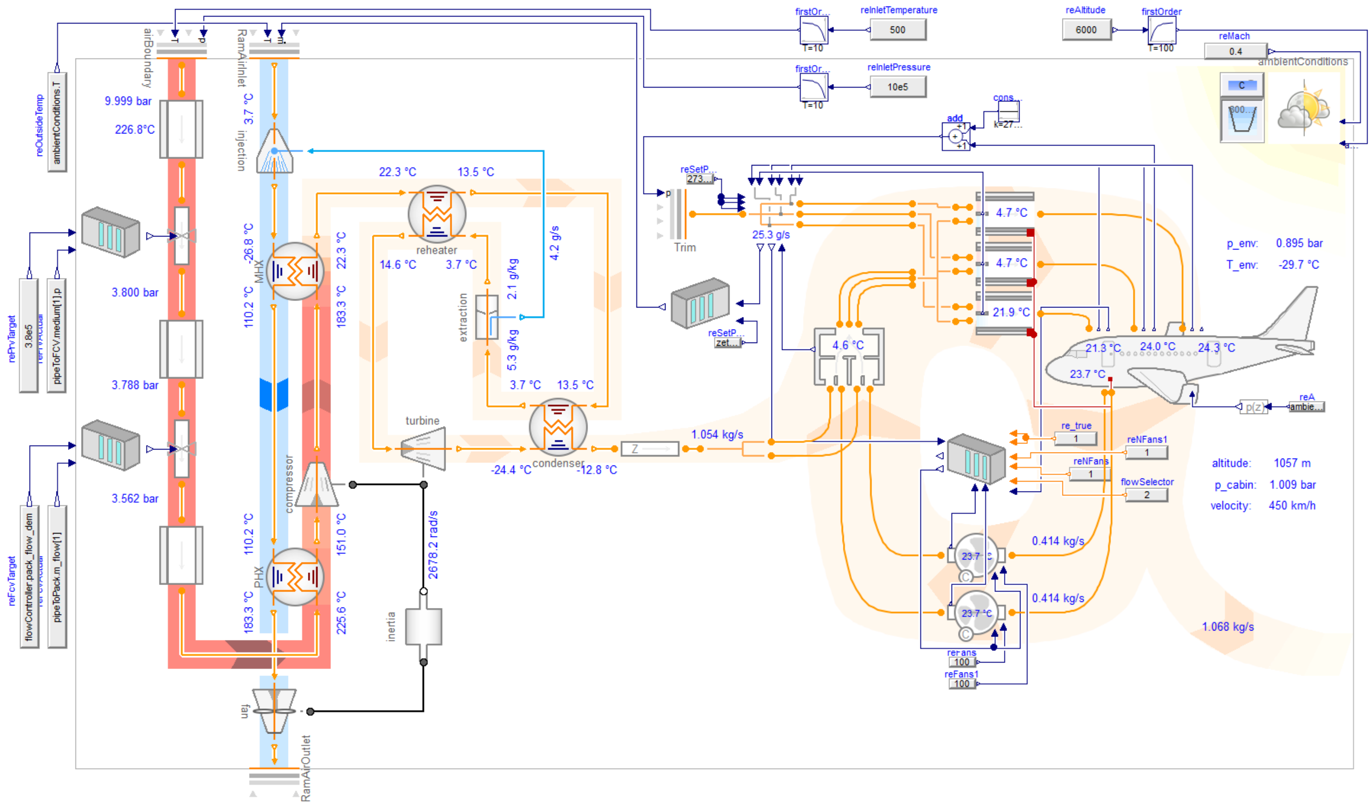

Fig. 1. Exemplary structure of a conventional ECS, as implemented in the equation-based modelling language Modelica

and demoisturized in the air conditioning pack. In the mixing chamber, it is mixed with filtered and recirculated air from the cabin. It is then divided into several ducts, mixed with small amounts of hot bleed-air if needed, and ducted to the different cabin temperature zones. While some of the cabin air is recirculated, the remainder is vented to the atmosphere and thereby cabin pressure is controlled.

Especially the first part of the ECS - the bleed-air system - is prone to limit cycle oscillations. This is due to the working principle of the corresponding valve actuators. The main element of the actuators is a pneumatic cylinder, which drives a piston that is connected to the valve disc of a butterfly valve. The air downstream of the valve disc is connected to the lower cylinder volume, thereby closing the valve if the downstream pressure is too high, or vice versa. This is illustrated in Figure 2.

To improve transient performance and to ensure zero steady-state control error, the pneumatic self-actuation is superimposed with an electronic control loop. The controller - usually in the form of a PI-controller - drives a small sub-actuator. It controls the mass balance in the upper cylinder volume by either driving upstream air into the chamber or by venting air into the environment.

In certain situations, the piston gets stuck due to friction. If the position the piston is stuck in a position other then the steady-state position, the transient response of the actuator results in a pressure build-up in one of the chambers. After a while, the resulting force is large enough to overcome static friction. The piston then overshoots the steady-state position and gets stuck again. The result is a repeating cycle.

Most bleed-air systems contain several valves connected in series. In the scope of this work, we take a look at an architecture using three valves: High Pressure Valve (HPV), Pressure Reduction Valve (PRV) and Flow Control Valve (FCV). The HPV is purely pneumatically actuated, the PRV additionally features an electronic control loop to regulate downstream pressure, the FCV regulates mass flow downstream while also employing an electronic control loop. The control problem therefore includes two electronic controller outputs, for PRV and FCV. For each control approach, seven variables were assumed to be measured: pressure values upstream and downstream of all valves, mass flow downstream of the FCV, and valve angles of PRV and FCV. This is illustrated in Figure 3.

2.2 Modelling and Simulation

To adequately predict the occurrence of limit cycles, a high-fidelity model of self-regulating pneumatic valves was created. For modelling, the equation-based modelling language Modelica (Mattsson et al., 1998) was used. For fluid-, thermal-, and multi-body-modelling, existing libraries were used (Otter et al., 2003; Modelica-Association, 2008; Casella et al., 2006). The actuator model is presented in detail in (Pollok and Casella, 2015) and (Pollok and Casella, forthcoming).

Based on that valve model, a system-level model of a bleed-air system was developed. It contains three valves, a large volume element representing the aircraft cabin and connecting pipes. The air conditioning pack as well as

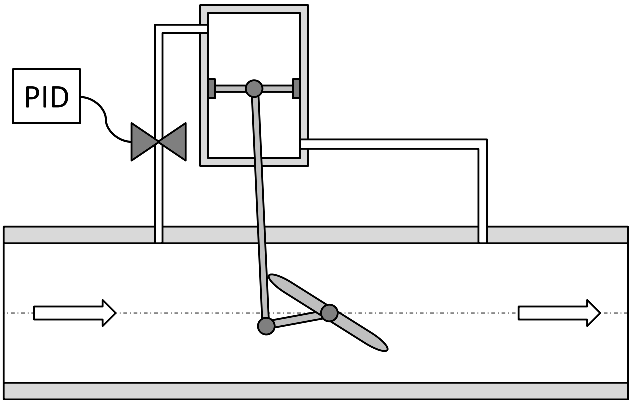

Fig. 2. Working principle of a self-regulating pneumatic valve

ducting is substituted with a pneumatic resistance to keep the model order moderate (75 continuous time states).

3. CONTROL STRATEGIES

In the aviation industry, each layer of complexity has to be traded against the necessary certification procedures as well as added weight and package dimensions. Therefore, controllers tend to be as simple as possible for the given performance requirements. Since decentralized PI-controllers are the state of the art for bleed-air systems, the approaches proposed in this work are kept as simple as possible.

Suitable control strategies for bleed-air systems are defined by the baseline control approach as well as an optional superimposed stiction compensation technique. In this work, we implemented, optimized and tested three control approaches as well as two stiction compensation techniques. Baseline controllers can be used without stiction-compensation, resulting in nine combinations. This is illustrated in Table 1.

Table 1. Combinations of baseline controller and stiction compensator

compensator	baseline controller →		
none	PI (state of the art)	LQG	MAP
Knocker	PI + K	LQG + K	MAP + K
I-Tuning	PI + I	LQG + I	MAP + I

3.1 Baseline Controller

PI: The state of the art is quite simple. Both PRV and FCV are controlled by a PI-controller. Manufacturers typically tune the PRV to be much slower than the HPV, and the FCV to be even slower. This is done to reduce interaction effects between the subsystems by frequency decoupling.

LQG: One alternative approach is to use centralized control for the electronically controlled valves. For the development of LQG-regulators a model linearisation was needed, which included two obstacles:

First, linearisation should be done in steady state, but the slope of the piston/cylinder-friction curve at zero velocity is not representative for the slope at typical velocities. Also, friction effects prevented any steady state from appearing. Therefore, the modelled friction was reduced to the viscous (linear) friction term. For this modified model, no oscillations occurred.

The second problem is related to the small control pipe that connects the main bleed mass flow to the lower cylinder volume. During steady state, the mass flow in the control pipe is equal to zero. The pneumatic resistance in the control pipe is roughly proportional to the velocity, at zero mass flow the resistance is vanishing. Any linearisation at zero mass flow does not represent the actual system adequately. For linearisation, we replaced the pneumatic calculation in the control valve with a linear dependency based on average absolute mass flows, during normal operation.

After linearisation, the model was augmented with an integrator as described in (Skogestad and Postlethwaite, 2007, p. 348), to enable integral action and zero steady-state error. The model was then balanced and model order was truncated to twenty states. This was based on a preliminary analysis, which promised good results between 15 and 30 states.

MAP: Another approach is to decrease interaction effects using some aspects of feed-forward control for the PRV. The steady-state PRV angle can be computed from exogenous variables only: in a small offline study, the resulting steady state valve angle (friction turned off) was computed for varying engine pressures. In the online system, the target angle is simply interpolated from those results. A simple three-point controller is used to set the valve angle to the interpolated target. The approach is called MAP since the inlet pressure is mapped to the target valve angle.

The hysteresis in this controller has to be chosen big enough to avoid limit cycles based on valve friction. This was tuned in some offline-experiments. The amplitude of the controller output was set to the electronic actuator limit.

One should note, that for this concept, a small hardware change is necessary. Without modifications, even with feed-forward electronic control, pneumatic self-actuation would still result in valve interactions. In this concept, the pneumatic self-actuation is switched off. A small on-off valve is integrated in the resistance between the downstream flow and the lower cylinder chamber. This valve is closed in normal operating mode, as a result, the actuator is influenced by electronic control only. The failsafe position of the valve is open, activating the self-actuation in pneumatic backup mode.

Aside from small aerodynamic effects from the moving air in the main pipe on the valve disc, there is no remaining interaction between the PRV and the other valves. The FCV is controlled with a PI-controller. With this concept, zero steady state error for the first controlled variable (pressure downstream of the PRV) cannot be guaranteed. This is usually not a substantial problem, as long as the pressure keeps below the pipe stress limits.

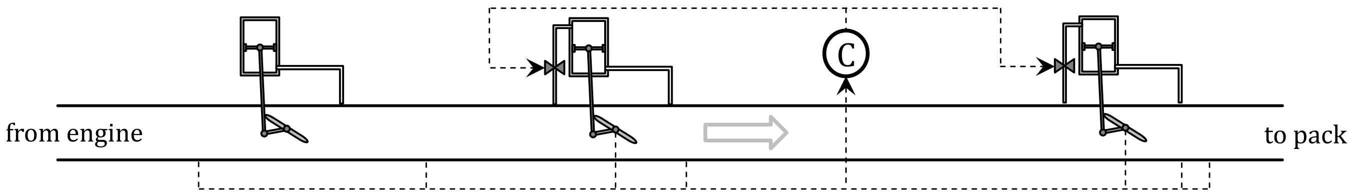

Fig. 3. Bleed-air system structure

3.2 Stiction Compensation

The two classic approaches to combat valve stiction are dithering and impulsive control. However, both approaches are not suited for pneumatically actuated valves, where the actuator input is essentially first-order filtered (Srinivasan and Rengaswamy, 2008).

In this work, we compare two stiction compensation approaches that are in principle suited for valves with filtered inputs. All baseline controller approaches were also implemented as is without any superimposed compensation, resulting in nine combinations in total.

Knocker: This technique was first proposed by Hägglund (2002). The controller output is superimposed with pulses that have the same direction as the first derivative of the controller output. This is illustrated in Figure 4.

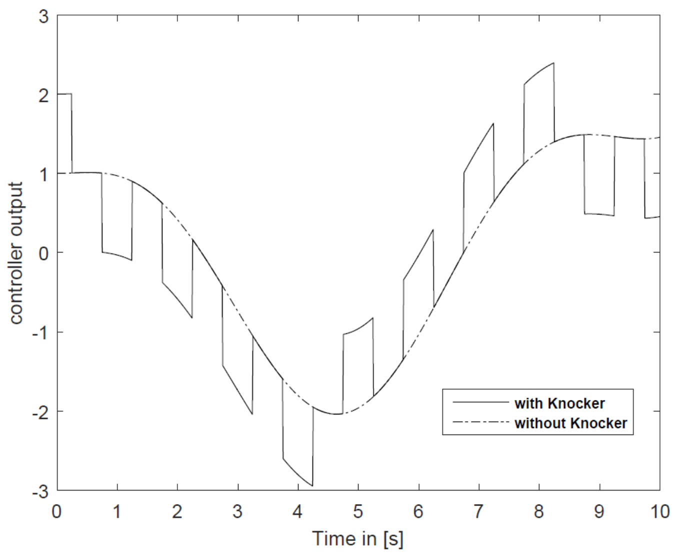

Fig. 4. Knocker approach for stiction compensation

Pulse height and pulse frequency are tuning parameters, that have to be adapted to the plant. The basic idea is that the energy content of a pulse is enough to overcome static friction.

I-Tuning: This technique was first proposed by Gerry and Ruel (2001) (as cited by Srinivasan and Rengaswamy (2008) and others). A variable gain is inserted prior to the integral element of the controller. The gain is calculated as

$$\alpha = [1 - exp(-ae^2 - b\dot{e}^2)]^2. \quad (1)$$

with the control error e and tuning parameters a, b. Essentially, integral action is continuously decreased as long as both control error and its first derivative approach zero. This is illustrated in Figure 5.

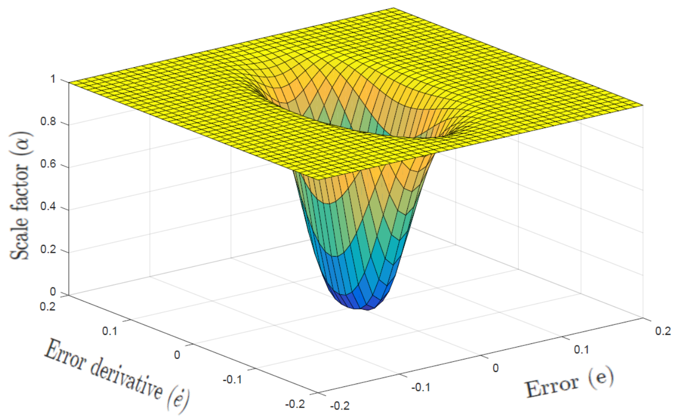

Fig. 5. I-Tuning approach for stiction compensation

4. METHOD

4.1 Evaluation Criterion

Before the strategies to control bleed-air systems were evaluated, a suitable evaluation criterion was defined. This enables quantifiable ratings of control strategies.

The used criterion penalizes valve movement and control error. It is divided into two parts. The first part integrates the absolute control error for both controlled variables: pressure downstream the PRV p, and mass flow downstream the FCV $\dot{m}$. Both are normalized against their target values:

$$J_1 = \frac{1}{T} \int_{t_1}^{t_2} \left| \frac{p_{error}}{p_{target}} \right| + \left| \frac{\dot{m}_{error}}{\dot{m}_{target}} \right| \mathrm{d}t. \quad (2)$$

The second part integrates the absolute velocities of the valve angles ϕ_i. This is a measurement for the total valve movement during simulation time:

$$J_2 = \frac{1}{T} \int_{t_1}^{t_2} |\dot{\phi}_1| + |\dot{\phi}_2| + |\dot{\phi}_3| \, \mathrm{d}t. \quad (3)$$

Both parts are combined using the weighted 2-norm. The weighting parameters w_i were chosen in such a way, that J_1 and J_2 would be equal for the state of the art system before optimization:

$$J = \sqrt{w_1 \cdot J_1^2 + w_2 \cdot J_2^2}. \quad (4)$$

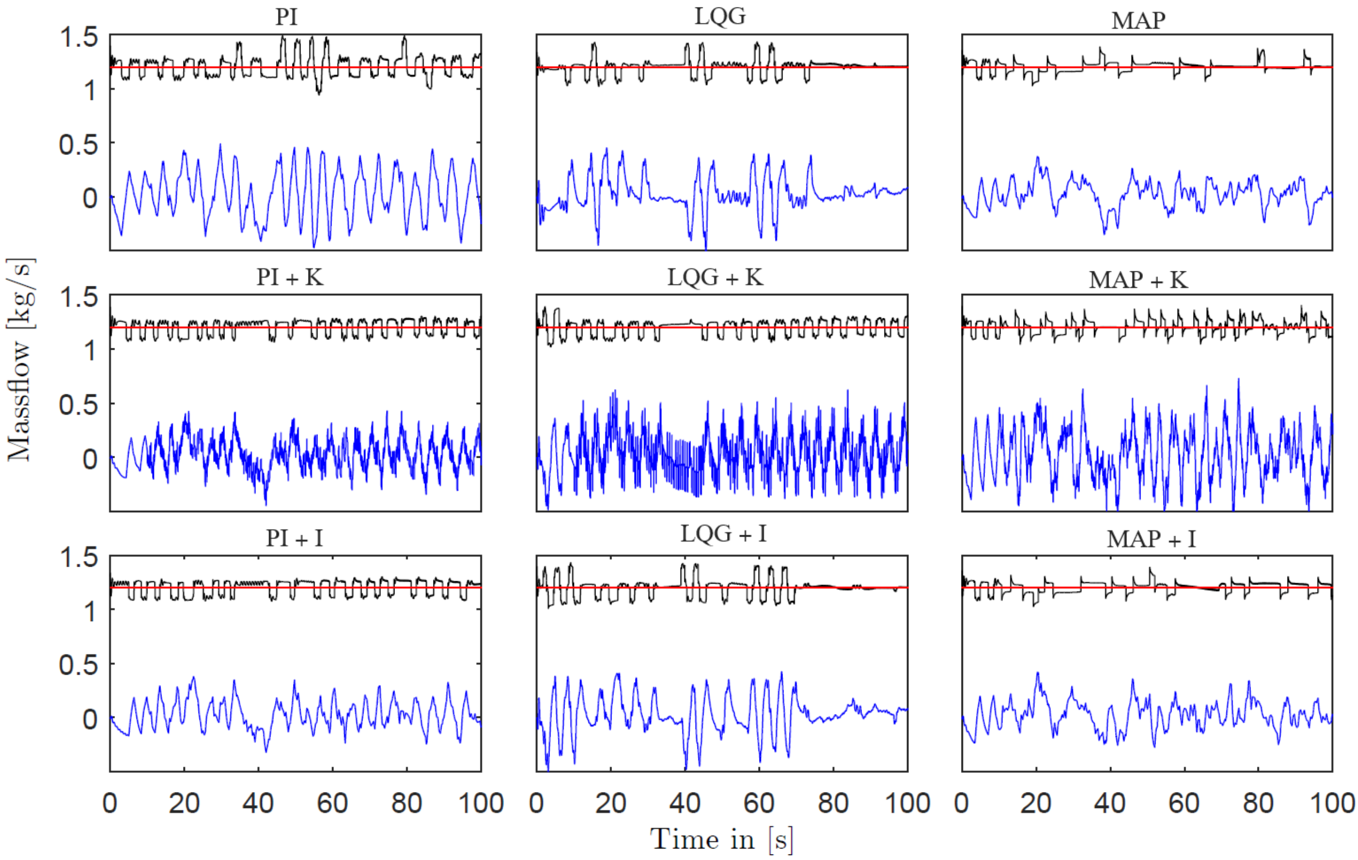

Fig. 6. Validation results for different control architectures: FCV massflow (black), constant target massflow (red), and scaled FCV control variable (blue)

4.2 Optimization and Validation

For each of the nine combinations of baseline controllers and stiction compensators as illustrated in Table 1, a Modelica model of the corresponding control structure was realized as well as a tuning script using Matlab.

Each combination was optimized using the pattern search algorithm (Hooke and Jeeves, 1961). Any function evaluation involved a model simulation. The chaotic nature of the physical system hindered optimization progress. To get meaningful results, bleed-air models have to be simulated for a large number of oscillation cycles, and a broad range of boundary conditions. For reasons of available computational power, a compromise of 100 seconds of simulated time was used, resulting in around 10 minutes of computation walltime.

During simulation, the engine pressure was ramped up from 5 to 20 bars. To keep the comparison fair, each of the nine combinations was granted 250 function evaluations. Using parallelization, total walltime was reduced to around two days. For comparison reasons, the state of the art architecture was optimized as well, since differences in behaviour between the model and the actual airplane could not be ruled out.

The nine optimized architectures were subjected to an independent validation run. This time, simulated engine pressure was changed during the simulation, as well as bleed-air system outlet-resistance. During validation, all measurements are superimposed by white noise, using the Modelica Noise library by Klöckner et al. (2014).

5. RESULTS AND DISCUSSION

In Figure 6, plots of the FCV mass flow are shown together with the FCV control variable.

The combination of PI-control and no stiction compensation can be seen as the baseline architecture. Rectangle-shaped oscillations are persistent with varying amplitude. The LQG-approach results in oscillations of similar shape, but there are oscillation-free periods. The control variable is much lower on average. For the MAP-approach, the shape of the oscillations changes considerably. Instead of the usual rectangles, the predicted mass flow features steps followed by decay-like behaviour. The amplitude of the oscillations is varying, but in general smaller then the amplitude of the PI- and LQG-approaches.

Adding a Knocker compensator results in some kind of regression to the mean. The behaviour of the PI-controller gets improved by decreased maximum oscillation amplitudes. The behaviour of the other approaches worsens by a higher occurrence of oscillations. Adding an I-Tuning compensator clearly improves the behaviour of the PI-controller. For the other approaches, the differences are small.

To quantify those results, the evaluation criterion as defined in Section 4.1 was evaluated for each combination of baseline controller approach and stiction compensation technique. The values after optimization and validation (shown after the arrow) are shown in Table 2. All values are given in percent and are normalized to the value of the criterion with the state-of-the-art controller during validation.

Table 2. Evaluation criteria after optimization and validation (less is better, normalized to state of the art)

	PI	LQG	MAP
none	69 → 100	54 → 64	34 → 56
Knocker	32 → 81	43 → 75	29 → 59
I-Tuning	32 → 73	37 → 61	37 → 54

Generally, performance drops during validation as expected. The drop is greatest for Knocker-augmented strategies, implying a low robustness for Knocker-based approaches.

The best, or lowest value after validation corresponds to a combination of MAP and I-Tuning. The criterion is 46% smaller than the state of the art upon validation. MAP standalone without any stiction compensation nearly reaches the same value. A sparsity-based argument can be made, that the small improvement given by the additional stiction compensator might not be worth the additional complexity. Also, the I-Tuning compensator adds an additional source of nonlinearity to the system, making it even harder to use frequency-based analysis techniques.

Centralized control by LQG shows promising results as well with an evaluation criterion 36% smaller than the state of the art. If zero steady state error for both controlled variables is needed, or if the proposed hardware change for the MAP-approach is prohibitive, then centralized control is a viable option. Again, adding an I-Tuning stiction compensator improves the behaviour, but not much. The considerations mentioned in the last paragraph still apply.

Performance of the Knocker compensator seems relatively poor during validation, but is much better during optimization: the best value of the evaluation criterion after optimization corresponds to a combination of MAP and Knocker compensator. This suggests poor robustness properties of the Knocker concept in the scope of this application.

6. CONCLUSION

For the control of bleed-air systems, valve interactions have to be considered carefully. This can be done, for instance, by centralized control or by feedforward control of one of the valves. Corresponding performance gains are substantial. Some superimposed stiction compensation techniques further improve performance only slightly, at the cost of additional complexity.

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