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Life-Extending Control of Reusable Rocket Engines

Michael Holmes,* Sekhar Tangirala,† and Asok Ray‡

Pennsylvania State University,

University Park, Pennsylvania 16802

Introduction

THE goal of life-extending control is to achieve a tradeoff between structural durability and dynamic performance of complex mechanical systems such as aircraft, spacecraft, and energy conversion systems. Typically, a controller synthesis procedure guarantees the stability of a closed-loop system within specified uncertainty bounds and, at the same time, ensures that the performance specifications are satisfied. Performance is usually defined in terms of command signal tracking, disturbance rejection, and/or control effort minimization. However, in general, reduction of damage occurring in critical plant components that are vulnerable to structural stresses is not explicitly taken into account in synthesis of the control law. Work reported by Ray et al.[1] shows that, using optimized open-loop feedforward control sequences, it is possible to substantially reduce the damage rate and accumulation in critical plant components with no significant loss in dynamic performance. However, such a damage-mitigation procedure is based on extensive off-line optimization and is applicable only when the operational maneuver is known a priori. Tangirala[2] presented a combined feedforward/feedback controller synthesis methodology applied to a laboratory test bed that achieves life extension and enhanced performance by using optimal open-loop input sequences along with a damage-mitigating output feedback controller.

This Engineering Note presents the results of ongoing research in life-extending control and is a continuation of the results presented in previous publications. Specifically, this Note presents a procedure for synthesis of life-extending feedback controllers and explores the feasibility of its application to a reusable rocket engine such as the Space Shuttle main engine. However, for brevity, the dynamic model of fatigue damage, discussed in detail in a previous publication,[1] is not presented. As an example of life-extending control synthesis, the results reported focus on 1) reduction of fatigue damage in the blades of the oxidizer (O_2) and fuel (H_2) turbines and 2) enhancement of engine performance by simultaneously minimizing the turbine torques and the output tracking errors of the thrust chamber pressure and the O_2/ H_2 mixture ratio. To realize different levels of performance/damage tradeoff, one performance controller and three damage-mitigating controllers are synthesized by using an induced L_2-norm method[3] applicable to sampled data systems.

Received Sept. 19, 1996; revision received Feb. 18, 1997; accepted for publication Feb. 19, 1997.

*Research Assistant, Department of Mechanical Engineering.

†Research Associate, Department of Mechanical Engineering.

‡Professor, Department of Mechanical Engineering, E-mail: axr2@psu.edu. Associate Fellow AIAA.

Synthesis of Life-Extending Feedback Controllers

This section summarizes a synthesis procedure for sampled-data output feedback life-extending control systems based on a linearized continuous-time model of a reusable rocket engine. A description of the rocket engine and derivation of the plant model are reported by Ray and Dai.[4] The plant model has 20 states and the two control inputs are the command signals to oxidizer valve actuators of the oxidizer (O_2) preburner and fuel (H_2) preburner. The inputs to the controller are the error in the thrust chamber pressure and the O_2/ H_2 mixture ratio.

The main objective of the control synthesis is to achieve a tradeoff between high system performance and low fatigue damage rate and accumulation in critical plant components. This is accomplished by appropriate selection of the (frequency-dependent) weighting functions used for controller synthesis. This section presents the design of four different controller modules that yield different levels of performance/damage tradeoff. The performance controller (PC) is designed without taking damage into consideration. The three damage-mitigating controllers (DMC1, DMC2, and DMC3) demonstrate three levels of tradeoff between performance and structural damage.

The nominal plant model used for the controller design is obtained by linearizing the nonlinear model of a reusable rocket engine[4] at a chamber pressure of 17.58 MPa (2550 psi), which represents the midpoint of the pressure ramp-up range from 14.48 (2100 psi) to 20.69 MPa (3000 psi) considered here. Referring to Fig. 1, the design goal is to find a stabilizing discrete-time controller so that the induced L_2-norm of the transfer matrix from w to $[z_1 \ z_2 \ z_3]^T$ is minimized. We use the method of Bamieh and Pearson[3] for L_2-induced synthesis for sampled-data systems, which makes use of a lifting technique to take intersample behavior into account in the controller synthesis procedure. The sampled-data problem is recast in terms of an equivalent discrete-time H_∞ synthesis problem. The scheme for the sampled-data controller design is shown in Fig. 1. The sampling interval is chosen as 0.002 s, which is fast enough to capture the thermal-hydraulic dynamics of the rocket engine without any appreciable aliasing in the output signal.

The performance weighting functions for penalizing the deviations of the actual thrust chamber pressure and O_2/H_2 mixture ratio from their reference trajectories are selected as

$$W_{\text{press}}(s) = \frac{k_p(s+\alpha_p)}{s+\beta_p} \qquad \text{and} \qquad W_{O_2/H_2}(s) = k_0 \tag{1}$$

where for DMC1, $k_p = 2000.0$, $\alpha_p = 7.5$, $\beta_p = 30.0$, and $k_0 = 1.0 \times 10^5$; for DMC2, $k_p = 4000.0$, $\alpha_p = 7.5$, $\beta_p = 30.0$, and $k_0 = 1.0 \times 10^6$; for DMC3, $k_p = 8000.0$, $\alpha_p = 7.5$, $\beta_p = 30.0$, and $k_0 = 2.0 \times 10^6$; and for PC, $k_p = 500.0$, $\alpha_p = 0.5$, $\beta_p = 1.0$, and $k_0 = 2.0 \times 10^5$.

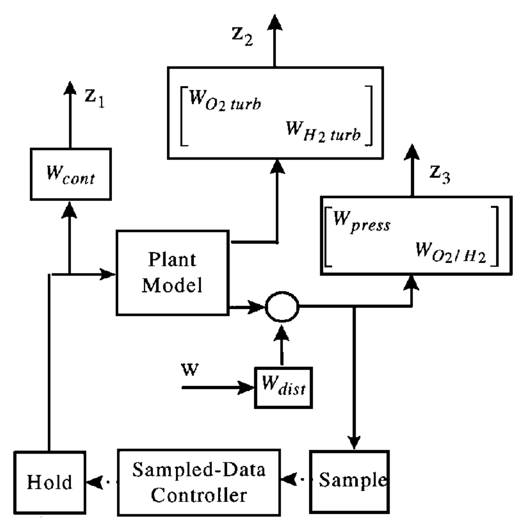

Fig. 1 Scheme for synthesis of the sampled-data controller.

A uniform scaling across the frequency spectrum is chosen for the O_2/H_2 ratio performance weight because deviations from the nominal value of 6.02 are undesirable at all frequencies. These weights and all the ones that follow were fine-tuned by trial and error to achieve the desired performance/damage characteristics.

To prevent the control valve actuators from saturating and chattering, each of the two control inputs is weighted by

$$W_{\text{cont}}(s) = 50{,}000\frac{s + 0.02}{s + 0.1} \tag{2}$$

and each of the two reference signals is modeled as a disturbance input with weight

$$W_{\text{dist}}(s) = \frac{0.001}{s + 0.001} \tag{3}$$

The torques generated by the oxidizer (O_2) and fuel (H_2) turbines are also weighted in syntheses of the damage-mitigating controllers in an effort to reduce high-frequency transients that may cause excessive fatigue damage in the turbine blades. In theory, specification of these weights along with the performance weights determines the tradeoff between dynamic performance and structural durability. These weights are

$$\begin{aligned} W_{H_2\text{turb}}(s) &= 5\frac{(s + 2\times 10^{-4})}{s + 0.1} \\ W_{O_2\text{turb}}(s) &= 50\frac{(s + 2\times 10^{-5})}{s + 0.1} \end{aligned} \tag{4}$$

To achieve ideal performance of the O_2/H_2 ratio, the O_2 turbine must have a larger bandwidth and therefore is subjected to more severe high-frequency vibrations than the H_2 turbine. Further, the O_2 turbine blades are longer than the H_2 turbine blades, leading to more damage accumulation even with a lower torque. To account for these factors, the weight on the O_2 turbine is made larger than that for the H_2 turbine at higher frequencies.

For the PC, the weights on the turbine torques in Eq. (4) are not used; however, the weights on the control inputs in Eq. (2) are included to avoid actuator saturation. For the three damage-mitigating controllers, DMC1, DMC2, and DMC3, the torque weights act to decrease control inputs and therefore prevent actuator saturation. High-frequency control inputs are needed to generate instantaneous torques from the turbines for driving the pumps, which must meet the large bandwidth transients of O_2 and H_2 mass flow rates. If the torques at high frequencies are heavily attenuated, control efforts at high frequencies are reduced and consequently control input weighting may not be necessary. In syntheses of the damage-mitigating controllers presented here, the torque weights are not changed and the tradeoff is achieved by tuning the performance weights in Eq. (1).

Results and Discussion

Figure 2 compares the thrust chamber pressure transients of the four controllers, DMC1, DMC2, DMC3, and PC, described in the preceding section. Figures 3 and 4 exhibit the fatigue damage accumulation of the four closed-loop systems in the O_2 and H_2 turbines, respectively. The three damage-mitigating controllers, DMC1, DMC2, and DMC3, achieve performance/damage tradeoff at different levels, with increasing chamber pressure performance causing larger amounts of damage accumulation. The PC yields the best tracking error of chamber pressure at the expense of largest damage accumulation. The transient response of the O_2/H_2 ratio, not shown in this Note, is within the acceptable limits of 6.02 ± 0.08 in all four cases.

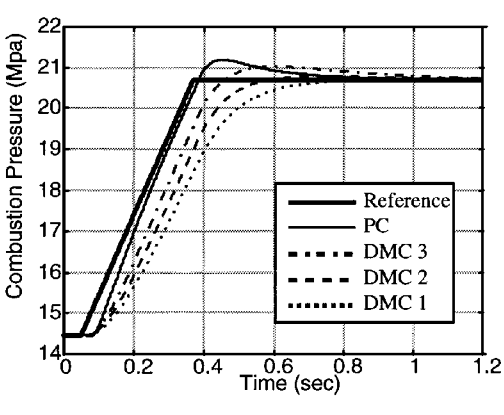

Fig. 2 Combustion chamber pressure profile.

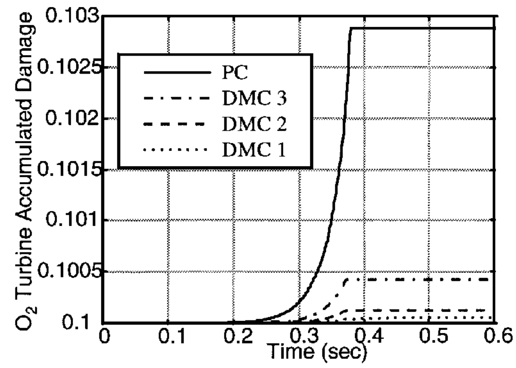

Fig. 3 Oxygen turbine blade damage profile.

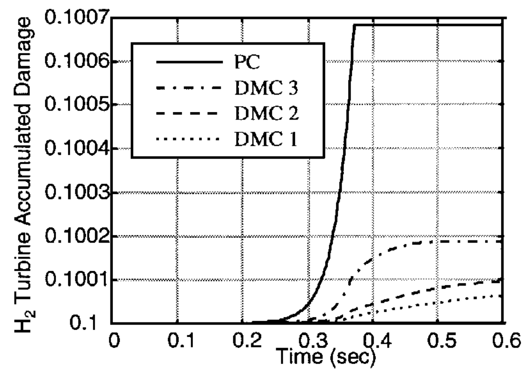

Fig. 4 Hydrogen turbine blade damage profile.

Conclusions

This Note presents a procedure for synthesis of life-extending controllers to achieve a desired level of tradeoff between structural durability and dynamic performance of complex mechanical systems such as aircraft, spacecraft, and energy conversion systems. Knowledge of damage-inducing variables is incorporated into the control synthesis procedure to mitigate structural damage regardless of the actual performance trajectory. As an example, a bank of controllers is synthesized for a rocket engine, similar to the Space Shuttle main engine, to achieve different levels of tradeoff between fatigue damage in the turbine blades and engine performance during upthrust transients.

Once a bank of damage-mitigating controllers is designed, the appropriate one can be selected based on the performance requirements of the mission and the allowable amount of damage accumulation in the rocket engine. For instance, if the engine is relatively new, the maximum PC can be used because the amount of damage accumulated over the course of the mission is unlikely to cause a catastrophic failure; however, if the engine has been used for a few missions and the damage accumulation has increased to a moderate level, one of the damage-mitigating controllers should be used depending on the performance requirements. The most logical first step is DMC3 because a considerable increase in structural durability is achieved for only a small decrease in performance relative to the PC. However, if the performance requirements for the particular mission are not very stringent, DMC2 or DMC1 may be more appropriate. As damage accumulates, DMC2 and finally DMC1 should be used to ensure safe operation.

The concept of life-extending control is potentially applicable to any system in which structural durability and dynamic performance are important issues and is capable of providing both financial benefits and enhancement of safety in many engineering applications.

Acknowledgments

This work was supported in part by NASA Lewis Research Center Grants NAG3-1240 and NAG3-1673. The authors acknowledge benefits of discussion with Carl F. Lorenzo of NASA Lewis Research Center.

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