4. Feedforward-Feedback Control by Nonlinear Programming and Structured Singular Value Approach,

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INTRODUCTION

In this paper, experiment results that verify the efficacy of the feedforward-feedback control (FF/FBC), synthesized by nonlinear programming and robust control techniques, are presented.

DISCUSSION

An alternative approach for synthesizing FF/FBC law was previously reported in a paper on the wide range operation of a pressurized water reactor[1] (PWR). In this proposed methodology, the feedforward control (FFC) input U^{ff}, indicated in Fig. 1, is optimized by nonlinear programming techniques,[2] and the dynamic output feedback controller (FBC) law is synthesized via robust control techniques.[3] The resulting FF/FBC system has optimized performance provided by the FFC and robustness provided by the FBC. A major advantage for synthesizing the FFC law by the nonlinear programming approach is that the FFC is determined with respect to a nonlinear plant model, including hard constraints on control and process vari-

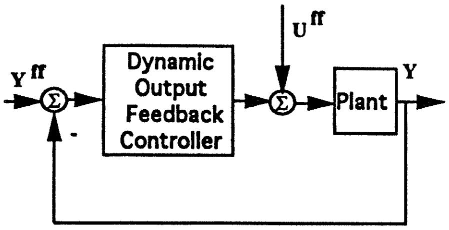

Fig. 1. Feedforward (U^{ff}) feedback control architecture.

ables. This off-line optimization procedure allows utilization of known plant dynamics and operational limits to better address plant performance and safety requirements. The prior computer simulation results have exhibited superior performance of the proposed FF/FBC system over FBC systems for a PWR system.

To further verify the efficacy of this methodology on a real-world application, an experiment was conducted at the Pennsylvania State University TRIGA reactor. The experimental goal was to quickly maneuver the reactor from an equilibrium condition at 50% power to a new equilibrium condition at 55% power while avoiding fuel temperature overshoot. To achieve this goal, the optimized feedforward signal U^{ff} (control rod speed Z_r) was based on minimizing the following discrete time objective functional J, using nonlinear programming:

$$J = \sum_{k=1}^{n} [400(\delta n_r^k)^2 + 0.01(\delta T_f^k)^2]$$

$$\text{subject to } Z_r - 0.2 \le 0;\ -Z_r - 0.2 \le 0 \quad ,$$

where the nominal performance for the system output Y^{ff} is represented by δn_r^k (the deviation of relative reactor power n_r from equilibrium at step k) and δT_f^k [the deviation from equilibrium core average fuel temperature (°C) at step k]. The form of this objective functional is similar to that used in observer-based optimal feedback control experiments conducted at the TRIGA (Ref. 4), except that no quadratic penalty is applied to the control input Z_r in the objective functional J. Alternatively, an explicit constraint on Z_r is readily incorporated in the nonlinear programming approach to determine the optimized FFC signal.

The precomputed optimized nominal trajectory Y^{ff} and TRIGA reactor experimental results Y are shown in Fig. 2. A fast response to new equilibrium conditions is accomplished through an initial significant overshoot of the reactor power signal. However, the goal of avoiding reactor fuel temperature overshoot was achieved. (For this particular demonstration, there was no goal restricting power overshoot; avoidance of temperature overshoot while achieving a fast response was the goal.) The discrepancy between the nominal trajectory Y^{ff} and reactor response Y is used in the feedback control path to accommodate the difference between the nominal plant model used to determine the optimized feedforward control signal and the actual plant dynamic characteristics.

CONCLUSION

The efficacy of the proposed FF/FBC synthesis approach has been verified by experiments on a reactor.

The major advantages of FF/FBC law established by nonlinear programming technique are summarized here:

1. The performance is optimized by an objective criterion (i.e., the objective functional) as opposed to ad hoc on-line tuning.

2. The FFC law is optimized with respect to the specified constraints and, therefore, will not lead to overly conservative solutions.

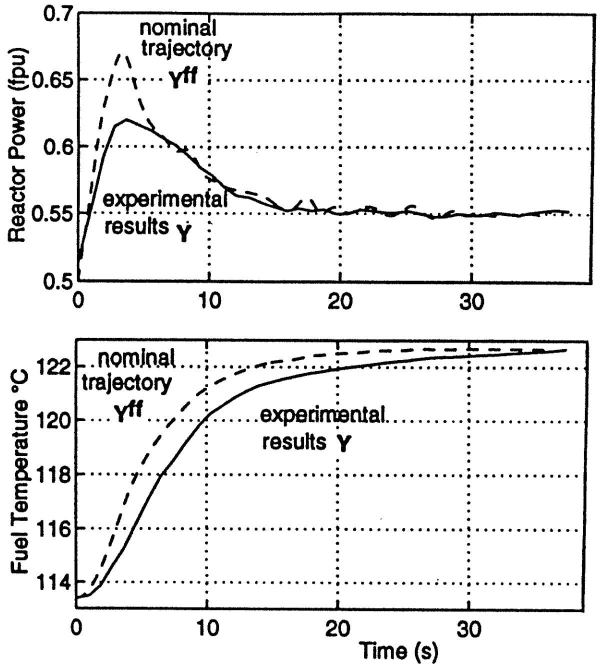

Fig. 2. TRIGA reactor experimental results demonstrating improved reactor temperature response of optimized feedforward-robust feedback control.

3. The FBC law is synthesized by robust control techniques, which guarantee system robustness for prescribed uncertainty or perturbations.

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