Consequences of Modular Controller Development for Automotive Powertrains: A Case Study

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Abstract

A modular controller structure for automotive powertrains has certain benefits. These include improved productivity through module reuse, seamless integration of new features, transparent removal of obsolete features, and module sharing across powertrain platforms. Modular architecture also potentially reduces the complexity in the design and calibration process, in that controller modules for different subsystems are developed independently. Due to the fact that the automotive powertrain system contains many highly interactive sub-systems, it is not clear that a modular controller development process can yield acceptable feedback controller performance with respect to emissions, fuel economy, and drivability. In this paper, we describe the engineering design issues associated with a decentralized development process, and the impact that the resulting decentralized controller has upon the dynamic response of the feedback system. We describe the possible detrimental consequences of subsystem interaction, and the potential of coordinated, multivariable feedback for alleviating these limitations. Control of a spark ignition engine incorporating variable camshaft timing is used as a case study.

1 Introduction.

The automotive powertrain controller is tasked with regulating exhaust emissions to meet increasingly stringent standards without sacrificing good drivability, and providing increased fuel economy to satisfy customer desires and comply with Corporate Average Fuel Economy (CAFE) regulations. First, designers are developing innovative mechanical enhancements of the spark ignition engine to achieve these goals. New features provide additional design parameters (control variables) needed to improve engine performance over a wide range of operating conditions. Tuning these parameters is a complicated problem, because they interact with various powertrain subsystems, such as the breathing process, combustion process, and exhaust generation process. Second, it is increasingly important to achieve control over transient behavior; for example, to rapidly reject disturbances in air fuel ratio (A/F) in order to minimize tailpipe emissions during transient operations.

Developing and implementing a powertrain management system is a complex and multifaceted engineering task. From the perspective of a controls engineer, it is natural to approach this problem by developing a dynamic model of the complete powertrain. A dynamic model facilitates study of such phenomena as transient response and subsystem interaction. The information thus provided enables the engineer to make informed decisions and tradeoffs that affect several components of the powertrain, with the design goal of achieving satisfactory overall system performance. On the other hand, the powertrain control problem is complex, and one way to manage this complexity is to divide it into subtasks. The goal of each subtask is to develop a controller module for a specific component of the powertrain subsystem, such as exhaust gas recirculation, spark ignition timing and A/F control. Modular controller development reduces complexity of the design, and yields a modular controller architecture. From the software standpoint, a modular architecture refers to a software organization consisting of a collection of independent program components with well-defined interfaces specifying the information flow across module boundaries. Such an architecture has many benefits: improved productivity through module reuse, seamless integration of new features, transparent removal of obsolete features, and module sharing across powertrain platforms. Additionally, maintainability is substantially enhanced in that modules can be modified independently of other parts of the powertrain control strategy. That is, one might remove and replace the EGR or fuel control module without affecting the rest of the strategy. The various advantages of modular controller design render it common practice for the design and calibration of control modules for different subsystems to be performed independently.

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A potential caveat associated with modular controller design is that it naturally leads to a decentralized control architecture. Were each of the powertrain subsystems associated with the software modules independent of the others, decentralized control would work well. Conventional automotive design practice has been to assume independence and apply, typically, classical control system design techniques to individual engine and powertrain subsystems. This is adequate for collections of subsystems where there is only weak dynamic coupling or where interactions can be minimized by de-tuning or calibrating a subsystem controller to avoid unintentional excitation. It may be appreciated, however, that this approach often results in less than optimal system performance and imposes a large calibration burden in time and effort for the very reason that there are in fact strong interactions among the various subsystems. These interactions limit the ability of decentralized control to achieve the level of performance obtained with centralized, multivariable control. Furthermore, even if a decentralized control strategy is satisfactory in implementation, it may prove necessary to coordinate the design and analysis of the individual control modules, as well as the calibration of their controller parameters.

The issues associated with modular controller development will be illustrated in subsequent sections using a system model that describes an engine equipped with variable cam timing. This system has significant interaction between the dynamics of the variable cam mechanism and those of the air fuel ratio subsystem. We shall discuss the relative utility of a modular, decentralized control architecture versus a multivariable control strategy. It will be shown that allowing the fuel command (used to regulate air fuel ratio) to depend upon the cam phasing results in smaller transients in air fuel ratio. This improvement in dynamic performance is at the expense of a more complex control architecture because the cam timing controller and the air fuel ratio controller are no longer self contained software modules. Finally, it will be argued that, even if a decentralized control design is possible, it is necessary to design and analyze the controller from a multivariable viewpoint in order to manage the tradeoff between software complexity and controller performance.

2 Background on the VCT Engine and the Control Problem.

The purpose of this section is to briefly explain the dynamics of a spark ignition engine equipped with a variable cam timing (VCT) mechanism, with special emphasis on the cam phasing mechanism and its interactions with several subsystems of the engine. Variable cam timing is a promising new feature for automotive engines because preliminary investigations ([8], [5]) show potential benefits in fuel economy combined with emissions reduction. It also obviates the requirement for external exhaust gas recirculation systems commonly used for NOx reduction. Cam timing is used to reduce the base HC and NOx feedgas emissions levels of the engine with respect to a conventional powerplant. By retarding the cam timing, combustion products which would otherwise be expelled during the exhaust stroke are retained in the cylinder during the subsequent intake stroke. The contribution of this diluent to the mixture in the cylinder suppresses NOx formation but also affects the mass charge in the cylinders, which in turn affects the air fuel ratio (A/F) response, and makes the A/F response highly coupled with the cam phasing activity. Another important feature of the variable cam timing is its effect on the manifold filling dynamics and ultimately on the engine torque response. Figure 1 shows the block diagram of the VCT engine. The static and dynamic relations, and its interactions are described in [7].

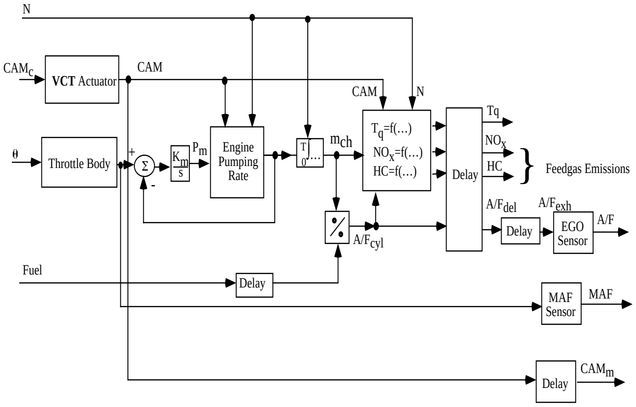

Figure 1: Block diagram of the VCT engine.

Due to the interactions between the subsystems, controlling the VCT engine might involve an extensive scheduling effort to define the new optimum operating points, combined with a laborious tuning process to achieve good transient performance. In the past, the development and implementation of control strategies on automotive engines equipped with new control actuators were based on the relative independence of the different subsystems at low frequencies. Today's stringent performance requirements no longer support this assumption. High bandwidth controllers are used to satisfy performance requirements, and this usually leads to operation in frequencies where there is a significant dynamic coupling between subsystems.

In particular, in a VCT engine cam phasing and fuel pulse-width affect feedgas emissions and A/F excursions. One could think of controlling cam phasing to minimize feedgas emissions (cam phasing loop), and regulating fuel pulse-width duration to minimize A/F excursions (fuel loop). This leads to two single-input single-output (SISO) control systems, which is the decentralized control approach. This approach initially ignores the interaction between cam phasing and A/F, which makes the two loops (cam loop and A/F loop) dynamically coupled over a large bandwidth. The feedforward control scheme designed in [7] ensures decoupling of the two subsystems in steady-state, but allows high frequency interactions, which, as shown later, will favor a centralized approach (i.e., use of a multivariable controller) to the VCT control problem.

In [7] we have scheduled the steady-state operating cam timing as a function of throttle position (θ), to minimize feedgas emissions while satisfying drivability and idle stability requirements for different engine speeds. The transition of the cam phaser between set-points during rapid throttle changes is a crucial parameter in the control design. Minimizing feedgas NOx and HC emissions favors instantaneous change of the cam phasing to the scheduled set-point. However, the cam phasing activity causes a high frequency disturbance to the A/F loop. Unfortunately the long delay (810 degrees) in the A/F measurement associated with the combustion-exhaust stroke and the transport delay in the exhaust manifold imposes a bandwidth limitation on the A/F loop. If the disturbance to the A/F loop caused by the cam activity is at high frequency, beyond the achievable bandwidth of the A/F controller, then the disturbance cannot be rejected. In this case, it is a common technique to slow down the cam phasing signals, i.e., de-tune the subsystem that causes the high frequency disturbance. This alternative, although consistent with current design practice, entails loss of the potential benefits of the VCT engine.

The goal of the control scheme is to minimize the tailpipe emissions which depend on (a) the feedgas emissions that the catalytic converter must process and (b) the efficiency of the catalytic converter (which is a function of A/F excursions from stoichiometry). Due to the interaction between the cam timing loop and the A/F loop we cannot simultaneously minimize (a) and maximize (b); this is because, maximum catalytic efficiency requires that A/F be held perfectly at stoichiometry, which in turn rules out moving the cam rapidly to reduce feedgas emissions. A dynamic model of the catalytic converter efficiency could help specify a rigorous tradeoff between the two bandwidths, because, after all, the ultimate goal is to minimize tailpipe emissions. Since it is difficult to identify an accurate and simple dynamic model of the tailpipe emissions, we selected the bandwidth of the cam phasing loop based on indications taken from engine-dynamometer data and experimental vehicle tests. The tests suggest that cam transitions are to be achieved within one engine cycle (720 degrees), so that we can realize the benefits of variable cam phasing early in the transient period. This dictates the lower bound on the cam phasing bandwidth. On the other hand, we have found that increasing the bandwidth much beyond this lower bound results in lean spikes in the A/F during “tip-in” (throttle steps), which result in unacceptable “hesitation” (torque drops). For the above reasons we chose one engine cycle (720 degrees) to be the required time constant of the cam phasing dynamics.

3 Multivariable and Decentralized Controller Design

The controller design considerations are : (a) There is a 810 degrees of delay in the A/F process. At 2000 rpm, this translates into a time delay of 0.0675 sec. The A/F bandwidth should not exceed 7.5 rad/sec since by using a Padé approximation for the 0.0675 sec delay we have the deleterious effects of a non-minimum-phase zero approximately at 15 rad/sec. (b) The required time constant for the cam phasing dynamics is 720 degrees (1 engine cycle). At 2000 rpm this corresponds to a time constant equal to 0.06 sec, which translates into a cam phasing closed loop bandwidth equal to 17 rad/sec.

Figure 2 shows the Bode gain plots of the plant linearized at 2000 RPM. Cam phasing is measured in degrees, A/F is dimensionless, and the fuel command is scaled so that a unit deviation in fuel causes a unit deviation in the A/F signal. The plant has a lower triangular form, i.e., there is no interaction between the fuel command and the cam phasing loop, since fuel charge affects the system downstream of the breathing process. In Figure 2 we can see the interaction term (p_{21}) between the cam phasing control signal and A/F measurement. The peak of the interaction term occurs at 20 rad/sec while we require the cam phasing activity to roll off after 17 rad/sec. Therefore, the control signal generated to force the cam phasing to track a command input will also produce a transient response in the A/F loop; in effect, the cam loop acts as a disturbance to the A/F loop. We thus see that we are faced with a difficult design problem.

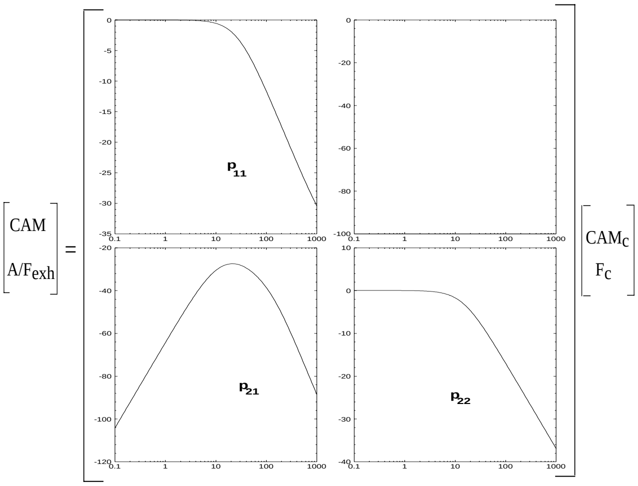

Figure 2: Bode gain plots of the linearized plant.

A few design iterations yielded the decentralized and the multivariable controllers, the Bode gain plots of which are illustrated in Figure 3. Both controller designs achieve the bandwidth requirement in the cam phasing loop, and provide adequate speed of response in the A/F loop.

Note that the diagonal elements of the two controllers are approximately identical. The reason for this will be-

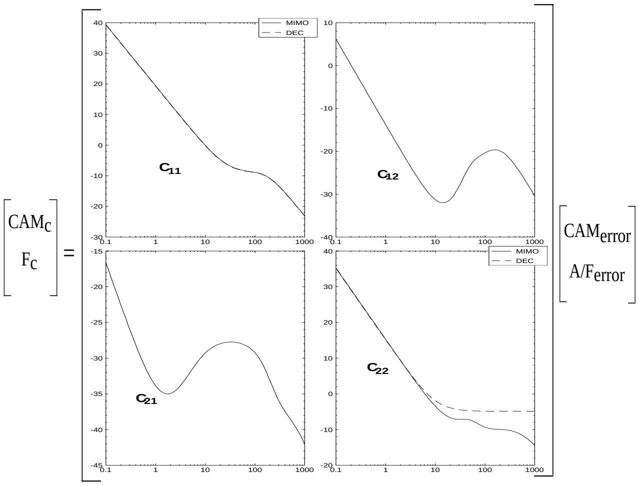

Figure 3: Bode gain plots of the two controllers.

come clear in the next section, where we see that the bandwidth specifications for the two loops essentially fix the bandwidths of the diagonal elements of the controller, independently of the controller structure.

Comparisons between the system response with the previously selected diagonal controller (see Figure 3), and the system response with a decentralized controller consisting of the diagonal elements of the multivariable controller, showed only negligible differences. Hence, for the rest of this study, we will simply compare and discuss the decentralized controller obtained by using the diagonal elements of the multivariable controller and the fully multivariable controller.

Figure 4 shows linear simulations of the output and control signals during various cam phasing step commands for the two different controller architectures. The A/F deviations for the multivariable control scheme are significantly better than those corresponding to the decentralized control scheme. Implementing the multivariable controller thus seems to be beneficial, but there are several questions we must address before we justify implementation of the multivariable strategy on a vehicle: How did the multivariable controller manage to reject the A/F disturbance faster than the decentralized controller? In which way did the multivariable controller reduce the interaction between the two loops? In the next section we identify the mechanism by which the multivariable controller achieves smaller A/F excursions during cam phasing transients.

4 Multivariable and Decentralized Controller Analysis

We begin by describing a design limitation present with decentralized control. Consider the decentralized control system in Figure 5. Topologically, the CAM loop acts as an output disturbance to the A/F loop. As noted in Section 2, there is no interaction from the A/F loop to the CAM loop.

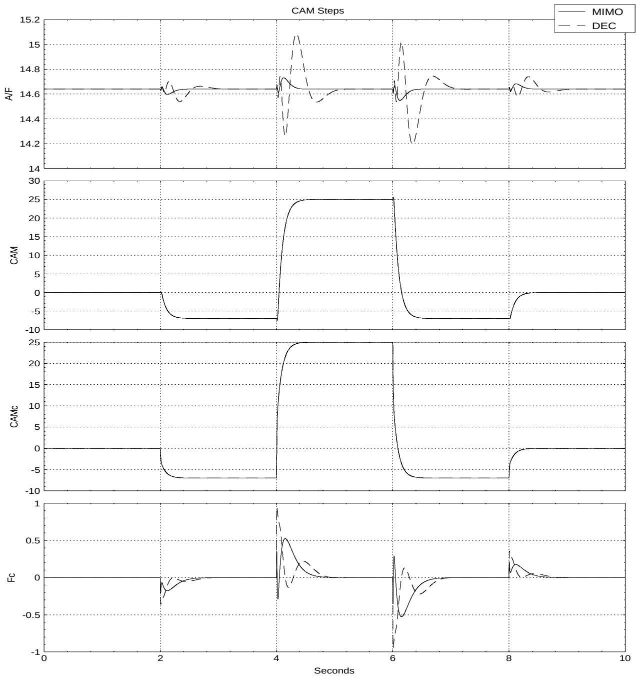

Figure 4: Linear simulation during cam phasing commands.

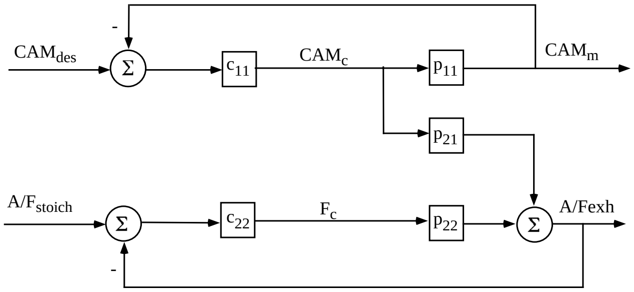

Figure 5: Block diagram of the decentralized control scheme.

Denote the sensitivity and complementary sensitivity functions for each loop by $s_{ii}(s) = (1+p_{ii}(s)c_{ii}(s))^{-1}$ and $t_{ii}(s) = 1 - s_{ii}(s)$, $i = 1, 2$. Then the transfer function describing the closed loop A/F response is given by

$$\begin{aligned} A/F_{exh}(s) &= t_{22}(s)A/F_{stoic}(s) \\ &+ s_{22}(s)p_{21}(s)\underbrace{c_{11}(s)s_{11}(s)CAM_{des}(s)} \end{aligned} \qquad (1)$$

The term underlined in (1) is equal to $CAM_c(s)$, the control signal in the CAM loop generated in response to a CAM command (CAM_{des}). As we have seen, the plant interaction (quantified by the transfer function $p_{21}(s)$), causes this signal to act as a disturbance to the A/F loop.

Suppose that this closed loop interaction results in unacceptable A/F transients. With a decentralized controller structure, there are two alternate approaches to reducing the interaction:

(i) Increase the bandwidth of the A/F loop, thus obtaining smaller sensitivity ($| s_{22}(j\omega) | \ll 1$), and greater disturbance attenuation, over a wider frequency range. This alternative is not feasible in the present problem, because of the time delay that limits the speed of response in the A/F loop.

(ii) Decrease the bandwidth of the CAM loop to obtain less control activity ($| c_{11}(j\omega)s_{11}(j\omega) | \ll 1$) at the frequencies of the problematic interaction. This alternative has been ruled out because it entails loss of potential benefits of the variable cam timing engine, as argued in Section 2.

The preceding analysis implies the existence of a tradeoff between CAM and A/F responses. Specifically, to reduce the undesirable effects of interaction from CAM command to A/F response, it is necessary to either reduce the bandwidth in the CAM loop, and/or increase the bandwidth in the A/F loop. Increasing the speed of the A/F response is not feasible due to the time delay; hence, the tradeoff is resolved by sacrificing CAM performance in favor of the A/F loop.

We have seen that a decentralized controller structure imposes a tradeoff between achieving the bandwidth specifications in the two loops. Let us now consider two mechanisms by which a MIMO controller can (potentially) mitigate such a tradeoff.

(1) Let the CAM control signal depend upon errors in both cam and A/F loops (the term (c_{12}) in Figure 6). Essentially, this strategy allows the controller for the CAM loop to achieve a compromise between regulating errors in the two loops and is an elegant alternative to the de-tuning practice (ii), that we mentioned above. In the present case, the delay in the A/F loop prevents this method from being useful because it is present in the response of A/F to both actuators. The significantly delayed A/F measurement cannot contribute information through the term (c_{12}) sufficient rapidly to slow the cam activity. Indeed, in Figure 4 we can observe the nearly identical cam phasing control signals issued by the two controllers. We verified that the MIMO controller does not make effective use of the A/F error in computing the CAM control signal by zeroing the term (c_{12}) of the MIMO controller and noting that closed loop performance is virtually unchanged.

(2) Let the fuel signal depend upon the error in both CAM and A/F loops (the term (c_{21}) in Figure 6). As depicted in Figure 7, this control strategy results in a feedforward path from the cam phasing error to the fuel command used to control A/F. The feedforward term (c_{21}) sends information to the fuel command about the cam phasing error, and this allows faster response during cam phasing transients. The disturbance imposed on the A/F loop by a command issued to cam phasing loop is shown at the following equation :

$$A/F_{exh}(s) = (p_{21}(s)c_{11}(s) + p_{22}(s)c_{21}(s))CAM_{error}(s) \tag{2}$$

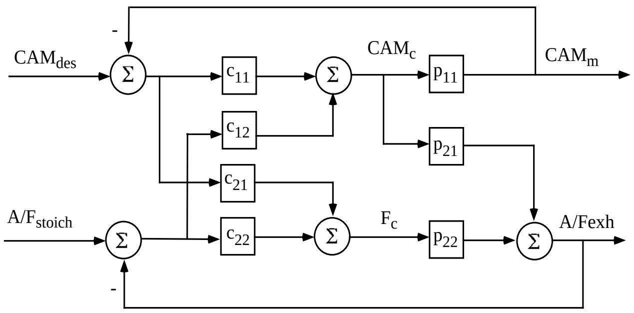

Figure 6: Block diagram of the fully multivariable scheme.

Note here, that the same disturbance for the decentralized controller (see Figure 5) is given by :

$$A/F_{exh} = p_{21}(s)c_{11}(s)CAM_{error}(s) \tag{3}$$

The multivariable controller can potentially reduce the coupling between the two subsystems by choosing the term (c_{21}) such that

$$| p_{21}(j\omega)c_{11}(j\omega) + p_{22}(j\omega)c_{21}(j\omega) | < | p_{21}(j\omega)c_{11}(j\omega) | \tag{4}$$

In Figure 8, we see that MIMO control reduces the peak in the closed loop response from CAM commands to A/F measurements.

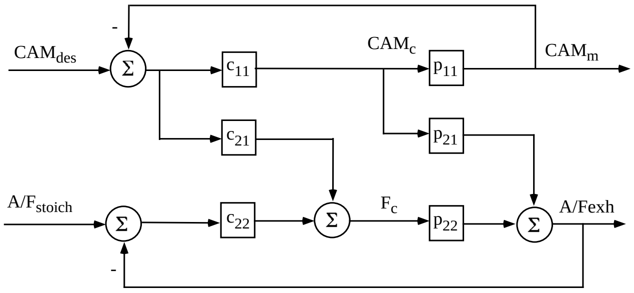

Figure 7: Block diagram of the simplified multivariable control scheme.

It is possible to interpret the action of the MIMO controller as partially decoupling the A/F response from the CAM loop. Indeed, setting the feedforward term equal to

$$c_{21}(s) = \frac{-c_{11}(s)p_{21}(s)}{p_{22}(s)} \tag{5}$$

achieves zero closed loop interaction from CAM to A/F. An alternate representation of the perfect decoupler (5) is depicted in Figure 9. With this topology, the CAM and A/F loops become completely decoupled, and the two remaining controller parameters, c_{11} and c_{22}, may be chosen independently. This controller design may be prone to robustness problems, since the term (c_{21}) is cancelling the undesired disturbance by inverting the signal along the path of the plant interaction.

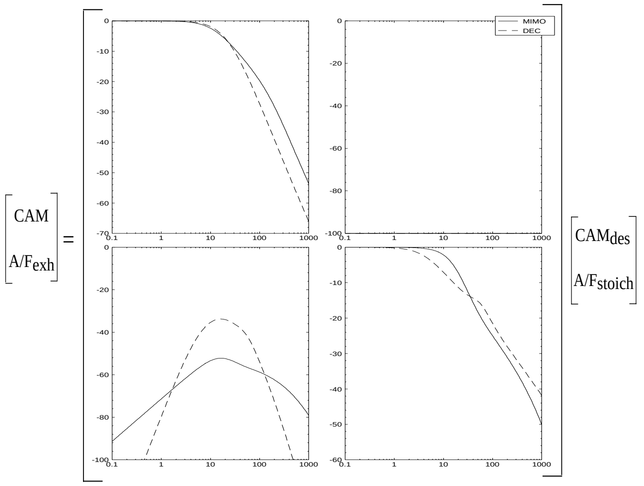

Figure 8: Bode gain plots of the closed loop transfer function.

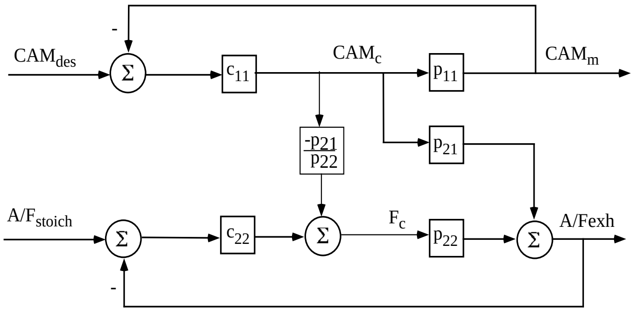

Figure 9: Block diagram of the decoupling controller.

In practice, there is no need to achieve perfect decoupling. Indeed, at lower frequencies, the integral action in the A/F loop achieves zero steady state error despite the interaction with the CAM loop. At higher frequencies, on the other hand, the CAM loop rolls off and thus does not produce a response in A/F. As we see in Figure 8, the MIMO controller merely reduces the peak due to the interaction, thus attenuating the effect of the CAM loop upon A/F without achieving total decoupling.

A potential difficulty with implementing the MIMO controller is that the feedforward term in the controller depends upon the plant; hence the performance improvements associated with MIMO control are sensitive to plant modeling errors. Indeed, the bandwidth limitation that precludes feedback from being used to reduce the effect of the CAM disturbance upon the A/F loop also prevents feedback from being used to reduce the effects of modeling uncertainty upon A/F.

5 Conclusions

We have described the impact of modular controller development upon the automotive powertrain control problem. Such impact is twofold: not only are controllers implemented in a decentralized fashion, but the control modules for each subsystem are designed and analyzed independently. As a consequence, the potentially deleterious effects of subsystem interaction may go undetected until relatively late in the design process. The case study presented in this paper demonstrated the potential benefits of multivariable control for an engine equipped with variable cam timing. By designing and analyzing a multivariable controller for the cam phasing and A/F loops, we showed that coordinated control for these two loops resulted in better A/F transient performance without detuning the cam phasing loop. A complete design, including a study of robustness and scheduling, remains to be completed. Even if the controller is eventually implemented in independent software modules, coordinating the design and analysis allows for a better assessment of the tradeoffs between dynamic performance in different subsystems. In particular, the effect of subsystem interactions emerges at an earlier phase of the design process.

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