Active Mitigation of Wind-Induced Response-Progress, Issues and Prospects

by

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ABSTRACT

The paper presents a brief overview of recent developments in the area of structural response control, with focus on active mitigation of wind-induced effects. Addressed are outstanding issues of response control and aspects specific to active control of wind-induced vibrations. Discussed are also control strategies, successfully implemented in non-civil engineering applications, which appear to be of tremendous, yet currently underutilized, potential for control of the response of buildings, bridges and other structures. A brief tutorial on optimal and robust response control is presented and application of robust control techniques is illustrated by considering a simple example. Optimal and robust control strategies are considered in analysis and design of an ideal model of a structure and a model subject to unmodeled dynamics and real parametric uncertainty. Reference is made to the existing analysis and simulation tools (Matlab/Simulink/μ-Tools) available to aid in robust controller design and validation. Potential impact of these techniques on the expected performance and reliability of practical active control systems for civil engineering applications is assessed. Finally, an initiation of a collaborative research, focused on application of robust active control for mitigation of wind-induced response is proposed.

KEYWORDS: active control; buildings; bridges; international collaboration; mitigation; μ-synthesis; response control; robust control; wind effects

1. INTRODUCTION

Focus on efficient utilization of land, space, and on more functional infrastructure is expected to sustain, and perhaps accelerate, the design and construction of buildings of increasing height, bridges of longer spans and other large-size structures. Material and labor cost considerations are expected to lead to buildings and structures of lower weight and to construction practices modeled on those developed and optimized in manufacturing industry.

Current designs of many light/flexible buildings and structures are often governed by serviceability considerations due to wind effects. The level of inherent structural damping of such structures is typically low and at times insufficient to bring the wind-induced response within the limits imposed by human comfort considerations. This situation has been recognized in design of tall buildings, long-span bridges and other wind-sensitive structures.

A number of schemes have been developed to mitigate structural response induced by natural phenomena (wind, earthquake, and wave loading) as well as man-generated effects, such as traffic induced vibrations and noise. This lead to emergence of the area of structural control, which has been recently attracting a growing interest worldwide, in the structural engineering community. Effort in this and related disciplines, in U.S., Japan and other countries, resulted in the development of innovative schemes for structural response mitigation. They include passive, semi-active, active and hybrid devices. A growing number of successful applications of passive systems, such as viscoelastic and tuned/liquid dampers, have been reported. Progress in this area

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has led to an intensified effort focused on systems incorporating active components and geared towards mitigation of earthquake and wind-induced response of civil engineering structures.

In the paper, we present a brief overview of recent developments in the area of structural control, with focus on active mitigation of wind-induced effects. Addressed are outstanding issues of response control and aspects specific to active control of wind-induced vibrations. Discussed are also control strategies, successfully implemented in non-civil engineering applications, which appear to be of tremendous, yet currently underutilized, potential for control of the response of buildings, bridges and other structures. A brief tutorial on optimal and robust response control is presented and application of robust control techniques is illustrated by considering a simple example. Optimal and robust control strategies are considered in analysis and design of an ideal model of a structure and a model subject to unmodeled dynamics and real parametric uncertainty. Reference is made to the existing analysis and simulation tools (Matlab/Simulink/μ-Tools) available to aid in robust controller design and validation. Potential impact of these techniques on the expected performance and reliability of practical active control systems for civil engineering applications is assessed. Finally, an initiation of a collaborative research, focused on application of robust active control for mitigation of wind-induced response is proposed.

2. RECENT DEVELOPMENTS IN STRUCTURAL CONTROL

It has been recognized that issues associated with response control of civil engineering structures (imprecise modeling, parameter changes due to aging, etc.) and stochastic variability of their loading require development of active control technologies (design/implementation) which may differ from those already established and validated in other disciplines. These issues have been the focal point of presentations and discussions documented in proceedings of meetings devoted to structural control, e.g. Leipholz (1980), Housner and Masri (1990), and Housner et al. (1994a), as well as recent workshops organized by the International Association of Structural Control (IASC), e.g. Joint US-Japan Workshop on Mitigation of Urban Disasters (1996), held in Kyoto, and Second International Workshop on Structural Control (1996), held in Hong Kong. They are also referred to in recent books on structural control, Meirovitch (1990), Soong (1990), and Gawronski (1996).

An increasing level of activities, recently observed in the area of structural control, may be partially due to a growing recognition of successful integration of control systems in other disciplines of engineering, including robotics and manufacturing, automotive and aerospace engineering, as well as computer and aircraft industry. One should also recognize a catalytic role in this area played by IASC (established in 1994) and impact in the U.S. of the National Science Foundation's Research Initiative on Structural Control. A large attendance (337 participants from 15 countries), and the number and scope (235 technical papers in 4 parallel sessions) of presentations during the First World Conference on Structural Control (WCSC), organized by IASC, Housner et al. (1994a), clearly indicate a growing interest of the civil engineering community in the area of structural control. One should also point out an increasing number of sessions on structural control, held during meetings of professional societies in the U.S., such as the ASCE Structures Congresses, e.g. Cheng (1996), as well as meetings in Japan, e.g. Yoshida and Nonami (1994).

The status of recent research and development in active control in the U.S. and Japan was summarized by Housner et al. (1994b) and Kobori (1994), respectively. Further updates on this topic were recently provided by Soong (1996) and Fujino et al. (1996). As pointed out by Housner et al. (1994b), significant progress has been achieved over the past 20 years in the area of active response control, both in the U.S. and Japan. However, the true potential of application of this technology in civil engineering has not been fully recognized yet, especially in the U.S. Progress has been noted in a number of areas, including: control algorithms and modeling, sensing and actuation, innovative control modes (hybrid and semi-active), implementation issues, and other related disciplines, such as system identification, structural damage detection and health monitoring. This effort has been carried out keeping in mind distinguishing features of civil engineering structural control, listed in Table 1, after Housner et al. (1994b). It follows that most of full-scale implementations of active control technology took place in Japan.

3. PROGRESS IN ACTIVE MITIGATION OF WIND-INDUCED RESPONSE

The status of research and development in the area of systems employing active components to mitigate wind-induced structural response can be assessed from papers presented during WCSC, Housner et al (1994a). We note that, with respect to mitigation of wind-induced response, effort was carried out along two paths: (1) systems designed to counteract wind effects only, and (2) systems capable of mitigating both wind and earthquake-induced response.

The examples of recent work from the first group include: active fin system for a building structure, Mukai et al. (1994), active appendaches for a deck of a long-span bridge, Wilde et al. (1994), counteracting time-dependent torque for a deck of a long-span bridge, Miyata et al. (1994), a boundary layer control method for a tall building, Kubo et al. (1994), tuned liquid dampers for tall buildings, Kareem (1994), tendon control for cable stayed bridges, Kobayashi et al.(1994), use of active vibration control for a bridge tower under erection, Sakai et al. (1994), application of hybrid mass damper system, Tamura et al. (1994), and others. Recent papers from the second group are primarily focused on practical aspects. They include reports on preliminary testing of systems under development and on effectiveness of the installed devices, monitored during strong winds and moderate earthquakes, Ohyama et al. (1994), Nakamura et al. (1994), Yamamoto and Aizawa (1994), Ohrui et al. (1994), Fujita et al. (1994), Petti et al. (1994), and Sakamoto et al. (1994). Current work and references published elsewhere and related to mitigation of wind-induced response, using auxiliary devices with active components, are discussed by Kareem and Tamura (1996), and by Soong (1990).

It follows from the reported studies that a significant progress has been achieved in the development and application of systems, employing active components, and designed to mitigate wind-induced response. Innovative concepts are being tested, while the developed systems have been installed at a number of sites, mostly in Japan. Some of the operational systems have already experienced strong winds (and moderate earthquakes) and they were found to be very effective in attenuating the structural response.

Active control was also employed in Japan to mitigate the response during construction of towers of suspension bridges, and to stabilize cranes during erection of tall buildings, Fujino et al. (1996). The resulting response attenuation lead to significant reduction in construction time and improved working conditions. As a result, application of active control was recommended for other construction sites. According to Fujino et al. (1996), active systems in Japan are currently installed in 20 commercial buildings and they were employed during erection of 14 bridge towers.

4. OUTSTANDING ISSUES OF ACTIVE MITIGATION OF WIND EFFECTS

As we mentioned earlier, critical issues of active mitigation of wind effects on structures and structural control in general, are directly related to the distinguishing features listed in Table 1. Most of the related topics have been addressed in published references and during conference presentations and discussions. In fact a number of workshops on structural control was held in recent years, with ample time allocated for discussion of these problems by working groups. Reports of these groups are included in workshop proceedings. Herein, we address some of the identified critical issues. Our discussion is largely based on a review paper by Housner et al. (1994b) and on reports of working groups of two workshops, Housner and Masri (1990), and Second International Workshop on Structural Control (1996).

As stated by Housner et al. (1994b), full-scale control installed systems "performed well for the purposes intended". Progress in active control technology for civil engineering structures has been made, but true potential of this approach for mitigation of wind (and earthquake) induced structural response has not been explored yet. Most of the developed systems are not capable of enhancing life safety against large environmental loads. Dominant control design practice is based on linear quadratic regulator formulation, which is not well suited for mitigation of response of civil engineering structures. This approach has been typically coupled with a linear model of a structure, which may be severely violated for the response levels associated with strong winds and earthquakes. Closer attention should be paid to issue of control robustness, in presence of imprecise modeling of structures, limitations of sensors and actuating mechanism, variability of the applied wind and other environmental loading, and effects of inherent noise. Optimal placement of sensors and actuators still remains an open question. New sensor and actuation technologies are desired. There is a need for more realistic model and full-scale experimental effort to assess effectiveness and practical aspects of control systems proposed for civil engineering applications. In addition, implementional issues require further attention. They include: system (software/hardware) integration, redundancy and fail-safe operation, system reliability and maintenance in context of intermittent operation and long dormant periods, system self-identification, diagnostic and corrective action. Strengthening of cross-disciplinary research and development is desired. Further effort should be also devoted to formulation of standardized benchmark problems and establishment of testbeds for experimental validation of control systems for specific civil engineering structures. A more rapid exchange of technical information and a closer cross-disciplinary and international collaboration are desired.

The above items have been originally identified in context of development and application of control systems for mitigation of structural response caused by earthquakes. However, most of these issues are equally relevant to systems designed primarily for mitigation of wind-induced structural response. The dominant difference between the two groups is the magnitude of the loading/response associated with severe wind/earthquake events and, in most cases, a relatively long prearrival time and duration of strong wind events.

We conclude that one of the most critical issues of active control for mitigation of wind-induced effects is imprecise modeling of a system (structure, sensors, actuators, presence of noise) and variability in wind loading. As we discuss this later, methods of optimal and robust control, advanced to address related problems in other disciplines, appear to be well suited to address this issue. They have been proven to be very effective in accounting for uncertainties in design of control systems in aerospace and aircraft industry. Application of this methodology has been also reported in civil engineering applications. However, it appears that the full potential of this approach has not been yet explored in structural control, including design of systems to mitigate wind-induced response. In this context, a brief tutorial on robust and optimal control is presented in the next section.

5. OPTIMAL AND ROBUST CONTROL

5.1 Introduction

The basic premise for optimal control design is to rearrange the problem into a canonical form, with a known plant model subject to unknown disturbances, and then to pose the controller design as an optimization problem for the unknown controller subject to desired closed-loop performance objectives. Note that this assumes that one has an accurate model of the plant to be controlled, although it may be subject to disturbance signals which are not well known.

The situation is illustrated in Figure 1. Here the exogenous disturbances to the generalized plant P are collected together in the (vector) signal w, and the signals to be controlled are in z. A feedback controller K takes measurements y from the system sensors and generates control signals u which are used to drive actuators. The disturbance signal w represents uncontrolled variables which are unknown a-priori, such as wind loading and/or sensor noise. The variable z represents signals we wish to keep small, such as structural response (displacement/acceleration) and/or weighted control effort. Note that in this setting P represents a model of the structure (e.g. building, bridge, tower, etc.), i.e. physical system, together with models of the sensors and actuators. Any desired weighting functions may be included in P. Hence the term *generalized* plant. In this context each control problem is rearranged to a disturbance rejection problem where we wish to design controller K to minimize the (closed-loop) gain from w to z, see Figure 1.

5.2 H_2 Optimal Control

Note that different optimal control problems can now be considered by specifying exactly what one means by "the closed-loop gain from w to z". If we denote T_{zw} as the system (transfer) from w to z in Figure 1, then we need some measure of the "size" of T_{zw}. This is provided in a precise mathematical sense by the notion of a norm. The classical H_2 optimal control problem measures the gain from w to z via the H_2 norm of the closed-loop system, which is given as

$$\| T_{zw} \|_2 \doteq \sqrt{\frac{1}{2\pi}\int_{-\infty}^{\infty} Tr[T_{zw}^{*}(j\omega)T_{zw}(j\omega)]\, d\omega}$$

where $T_{zw}(j\omega)$ = the (complex) transfer matrix of the system, and $(\ )^{*}$ denotes complex conjugate. One can give this mathematical description some physical meaning, by a number of equivalent definitions: H_2 optimal control minimizes the power of the output signal z, assuming the disturbance signal w is zero-mean white noise. Thus H_2 optimal control assumes that the disturbance signals are a-priori known stochastic signals , see Zhou (1996) or Anderson and Moore (1990) for an in-depth treatment of H_2 optimal control. Note that the assumption of uncolored noise is not restrictive, since one may easily weight these signals, and absorb the weights into P, to better represent energy (power spectrum) of disturbance (e.g. wind loading). There are also equivalent characterizations of the problem in terms of impulse disturbance signals and non-zero initial conditions. In addition, there are a number of equivalent formulations for this control problem. For instance the Linear Quadratic Gaussian (LQG) problem is posed in terms of a penalty function involving the integral of a weighted quadratic combination of the outputs (structural response, accelerations) and control signals (due to actuators), but this procedure is readily shown to be equivalent to the above.

The solution to the H_2 optimal control problem satisfies a well-known separation structure, in that the optimal control for the above output feedback problem is composed of two parts. (This is also referred to as the certainty equivalence principle, see Zhou (1996) for detail.) One may first solve the corresponding Linear Quadratic Regulator (LQR) or state feedback problem, which assumes that all the states of the system can be measured. This solution is referred to as the optimal state feedback *gain*, since it involves no dynamics. One may then solve an estimation problem to optimally estimate the system state from the outputs. This requires a dynamic estimator referred to as a Kalman filter. The composition of these two stages generates the optimal H_2 or LQG output feedback controller.

Note that each of these two stages requires one to generate and solve the appropriate Riccati equation, so that the overall H_2 problem requires the solution of two Riccati equations. This can be accomplished invoking commands of readily available software, such as Matlab. There are standard Matlab toolbox commands to do this. For instance the Control toolbox includes the commands *lqr* (solves the LQR problem for the optimal state feedback gain), *lqe* (solves the Kalman filter problem), and *reg* (combines the state feedback gain and Kalman filter to provide a controller solving the LQG problem). The μ-Tools toolbox includes the command *h2syn* which combines these stages into one command solving the H_2 output feedback problem directly as posed in Figure 1.

This design procedure is capable of producing high performance controllers (optimal in the above sense) for *known plants*. However, it is important to note that this procedure does not include any robustness requirements, since it is based on the setup in Figure 1, which does not include any unmodeled dynamics. Indeed for H_2 optimal control even the disturbance signals are in some sense assumed to be known (with characterizations either as white noise, or an impulse signal, or a non-zero initial condition). However, one might hope that the resulting controller has some desirable robustness properties, and in fact this turns out to be true for the optimal LQR controller. (This design can be guaranteed a-priori to have a gain margin of at least 6dB, and a phase margin of at least 60 degrees.) These results generated a good deal of excitement when they first appeared, since they seemed to indicate the inherent robustness of H_2 optimal control. Note, however, that the LQR problem requires that all the states are available for feedback, which is not usually the case in practice. One might further hope that these results carry over to the more practical output feedback or LQG case, where the states are estimated from the measured outputs. Unfortunately it turns out that this is not the case. It is shown in Doyle (1978) that the above robustness properties disappear for the output feedback case, and in fact H_2 optimal control designs provide no a-priori robustness guarantees whatsoever.

5.3 H_∞ Optimal Control

An alternative to H_2 optimal control is provided by H_∞ optimal control. This control philosophy is based on the exact same setup as before (see Figure 1), but with a different choice of norm, namely the H_∞ norm

$$\|T_{zw}\|_\infty \doteq \sup_{\omega} \bar{\sigma}[T_{zw}(j\omega)]$$

where $\bar{\sigma}$ denotes the largest singular value. Note that mathematically the H_∞ norm is simply defined as the peak value of the frequency response of the system. It turns out that this is equivalent to minimizing the energy of the output signal z, assuming that the disturbance signal w can be any signal of no more than unit energy. Thus the disturbance signals are not assumed known a-priori, but rather can take worst-case values from this allowed set. The interpretation of the H_∞ norm as the maximum energy-to-energy gain of the system is very appealing (and it provides many interesting connections to minimax and game-theoretic problems).

The H_∞ optimal control problem turns out to be more mathematically involved than the H_2 problem, and the solution was recently obtained in Doyle et al. (1989). Once again it requires solving two Riccati equations, although their solution is not so (numerically) straightforward as in the H_2 case. There is also a form of the separation principle for the solution, but it is more subtle than in the H_2 case. Once again powerful Matlab based tools exist for H_∞ optimal control design, and the μ-Tools toolbox command *hinfsyn* solves the output feedback H_∞ optimal control problem.

Note that for H_∞ optimal control the disturbance signals are unknown a-priori and may take worst-case values. Thus the controller is in some sense playing a game. It seeks to minimize the energy of the output signal z via the control signal u. At the same time Nature takes the role of the opposing player and attempts to maximize the energy of the output signal z via the disturbance signal w. This interpretation has led people to believe that H_∞ optimal control is a robust design procedure. However, it is important to note that, although the disturbance signals are unknown, the plant is completely known in this formulation. Once again the design process does not account for unmodeled dynamics at all, and so in fact H_∞ optimal control is not a robust controller design procedure. Indeed there is nothing to show that an H_∞ optimal control design will be any more robust than an H_2 optimal control design. However, the inclusion of worst-case disturbances can be used to combine H_∞ optimal controller design with other techniques, so as to yield a design process for robust controllers, and this is outlined in the next section.

5.4 Robust Control - μ Synthesis and *D-K* Iteration

The optimal control techniques described in the preceding sections were developed to provide high performance controllers for systems where a high fidelity mathematical model is available. In particular, they have been used extensively in the aerospace industry. In many situations, and in particular for civil engineering structures, such high fidelity models are not available. In this case it may happen that a control design (possibly an optimal one) performs well in simulation on the available nominal model of the system, and performs poorly (may not even be stable) when implemented on the real physical system. The problem arises from the fact that the model is not sufficiently accurate in some aspect, and the high performance controller design is attempting to exploit knowledge of the system that is incorrect! The theory of robust control attempts to take into account these inherent inaccuracies in the model, and to provide systematic analysis and design techniques in the face of this "uncertainty."

In order to deal with this phenomenon we consider the canonical framework illustrated in Figure 2. Once again it is easy to rearrange many problems into this framework and we will present a simple example to illustrate the approach. Note that now the system is augmented with a perturbation or uncertainty block Δ. This uncertainty block captures any knowledge we have about the size and placement of model perturbations entering the system. Note, however, that we will not assume specific knowledge about the dynamics of Δ, but merely bounds of the size of its components. It is important to note that the inclusion of model perturbations or unmodeled dynamics in our analysis and design framework is a significant departure from merely allowing unknown disturbances. The effects of unmodeled dynamics on a system cannot be captured as simply another form of disturbance signal. For instance, while disturbance signals can degrade the performance of a nominally closed-loop stable system, they can never destabilize it. On the other hand model perturbations can not only degrade performance, but they can even drive the closed-loop system unstable.

Once again we need a characterization of size for the blocks of Δ, and it turns out that a convenient one is the H_∞ norm. Since this norm captures the maximum energy-to-energy gain of a system, it can capture the maximum signal amplification that a perturbation can inject into a system. One can use this information to develop analysis tools for the following questions:

Robust Stability: How large a perturbation can the system tolerate and still maintain closed-loop stability?

Robust Performance: How large a perturbation can the system tolerate and still maintain the desired closed-loop performance level? Here performance is measured via $\|\tilde{T}_{zw}\|_\infty$, where $\tilde{T}_{zw}$ is the *perturbed* closed-loop map from w to z.

The answers to these questions require some fairly involved mathematics, and the required computation is referred to as μ-analysis (also structured singular value analysis). A survey of these techniques is provided in Packard and Doyle (1993) for unmodeled dynamics and Young (1993) for parametric uncertainty. It turns out that μ is not amenable to exact computation, but there are readily computable upper and lower bounds, which usually provide an approximation sufficient for engineering purposes. Once again the practitioner need not be familiar with the details of the solution and the Matlab μ-Tools toolbox command *mu* readily facilitates robust stability and performance analysis.

Once μ-analysis methods were established, it became natural to consider the μ-synthesis question, namely that of designing a controller K so as to optimize robust performance. Note that this amounts to an H_∞ optimal control problem, but now for the perturbed closed loop map $\tilde{T}_{zw}$. In this setting both the disturbance signal w and the model perturbation Δ are unknowns which may assume worst-case values. Mathematically speaking the μ-synthesis problem is much harder than H_2 or H_∞ optimal control, both of which are convex optimization problems for which the global optimum is readily found. The μ-synthesis problem is not convex, and we are forced to resort to approximate methods. A commonly used approach is the *D-K* iteration procedure. This process first approximates μ with its upper bound, which takes the form of an H_∞ norm, scaled by a certain D-operator. The synthesis problem thus becomes a scaled H_∞ optimal control problem and the *D-K* iteration attempts to solve this by alternately computing the D scaling from μ-analysis and the controller K from an H_∞ optimal control problem. The procedure is detailed in Stein and Doyle (1991). This iteration is implemented in the μ-Tools command *dkit*, which can be run in batch mode, or allow the user to interactively specify the iteration parameters.

It should be noted that this design process is not as straightforward as H_2 or H_∞ optimal control. Although software is available to implement the mechanics of the method, there are certain subtleties to the procedure, and typically the user must have some familiarity with these to produce an acceptable design. However, the payoff for this is a true robust controller, with a certain level of guaranteed robust performance. This means that the controller will guarantee closed-loop stability, and it will keep the energy of the output signal z below a specified level, despite any disturbance signal w, and any unmodeled dynamics Δ (both of the appropriate size). This guaranteed insensitivity of the design (in both stability and performance) to both disturbance signals and modeling errors is crucial to being able to provide high performance designs in a practical setting. The goal is to provide a controller which works well, not only in simulation, but also on the actual system, despite fairly crude models for the system (and unknown disturbance signals).

5.5 Illustrative Examples

In this section we offer some examples of applying the above techniques to structural control problems. A simple tutorial problem is considered first. Next we review two more realistic examples from the literature.

5.5.1 Tutorial Problem

In this section we consider a simple vibration suppression problem. We assume a one-mode representation of wind-induced vibrations of a slender structure (e.g. tall building, bridge tower, etc.). Let us suppose that the fundamental natural frequency of the structure is equal to 0.2 Hz and that its (viscous) damping ratio is 2%. It is further assumed that the considered mode of vibrations is linear and that the structure can be represented by a rigid body elastically supported at its base. Moreover, we assume that acceleration at the rooftop and a torque actuator (at the structure base) are available for feedback control. In order to keep the example as simple as possible, no dynamics are assumed for the sensor and actuator, although the measurement signal (acceleration) is subject to additive white noise. The wind-induced overturning moment is represented by white noise. A block diagram for this setup is shown in Figure 3. Of course this setup is very simple, and does not capture all the features required for a realistic design (e.g., computation delay, complex dynamics), but it will serve here to illustrate the application of optimal and robust control techniques.

In order to apply optimal control we first need to state our design criterion in the framework of

Figure 1. The Simulink model in Figure 4 shows our design model, with assumed numerical values and weighting and penalty functions. The generalized plant P can be extracted from this via the Simulink command *linmod*. Note that this plant includes weighting functions on the disturbance signals, and penalty functions for the outputs we wish to control. Again a fairly simple set of the (weighting/penalty) functions were selected. The same setup was used for both the H_2 and H_∞ optimal control designs. In practice one would probably choose different weights for each case, but we used the same weights for ease of comparison. We designed an H_2 and H_∞ optimal controller for this problem setup using the Matlab commands outlined earlier. Both controllers were of 4th order and stable, and they both stabilized the nominal closed-loop system, as was verified by eigenvalue analysis.

Robust controller design via μ-synthesis requires developing a design model in the framework illustrated in Figure 2, where an uncertainty structure is now included. The Simulink model in Figure 5 represents our design model. Note that again, for ease of comparison, we have selected the exact same weighting/penalty functions to specify the desired performance. However the design model now also includes a robustness requirement via the weighted uncertainty structure. This model was used to implement a μ-synthesis design via D-K iteration, as described earlier. The resulting controller was of 6th order and stable, and it stabilized the nominal closed-loop system.

The Simulink simulation model in Figure 6 was run for the open and closed loop configurations. Note the presence of "On/Off" blocks, which are set to 1/0 as required to switch in/out certain components: the controller (Feedback Compensator) and the perturbation block (High Frequency Unmodeled Dynamics). Note also that scaling blocks are included to convert the normalized units of the model into physical units for a considered hypothetical large structure.

The results for the case with the perturbation block turned-off are shown in Figures 7 through 10. They include an open-loop run, Figure 7, and three closed-loop simulations. Two of the closed-loop cases resulted from invoking H_2 and H_∞ controllers, Figures 8 and 9. The third case, Figure 10, corresponded to the robust (μ-synthesis) design. The resulting 2-norms of each signal are collected in Table 2 (the 2-norm corresponds to the energy of the signal). It is seen that the H_2 and H_∞ optimal controllers achieve high levels of performance for the nominal closed-loop system, with the H_∞ controller being slightly more aggressive in terms of control effort, and consequently achieving slightly higher performance. The μ-synthesis controller is less aggressive than the optimal control designs, and it achieves a lower level of performance for the nominal system, though it is still fairly high.

In order to illustrate the robustness properties of these controllers, a perturbed system was considered. (The μ-analysis techniques were used to determine a suitable problem perturbation.) The frequency response plots for the open-loop plant and the plant perturbation are shown in Figure 11. Note that the perturbation is much smaller than the original plant (H_∞ norm of plant is 25, versus 1.43 for the perturbation), and its effect is only significant at high frequency. The perturbation is of 4th order and it is stable.

The performance of the perturbed plant was simulated using the Simulink model in Figure 6, with the perturbation block (High Frequency Unmodeled Dynamics) switched on. The results for open-loop, and all three controllers, are contained in Figures 12-15, and the signal energies are tabulated in Table 3. It can be seen from the open-loop response, Figure 12, that the plant response contains now more energy at high frequency. The effect of this on the H_2 and H_∞ optimal controllers is devastating, as shown in Figures 13 and 14. It can be seen that the H_2 controller is barely stable, Figure 13, and is not able to deliver any performance (actually it is worse than open-loop), and the H_∞ controller is unstable for the perturbed closed-loop system,

Figure 14. In contrast, the μ-synthesis controller maintains stability, and is still able to deliver a reasonable level of performance, Figure 15 and Table 3.

The above example illustrates some of the methodologies of optimal and robust control design and the performance/stability properties of the resulting control systems. However, one should bear in mind that it is only a simple tutorial example and one should refrain from generalizing conclusions from this example to real, more complex systems. In the next section we briefly discuss (with references) two examples where the ideas of optimal and robust control have been applied in a practical setting.

5.5.2 Application Examples

The control of a large flexible structure, the Langley NASA Minimast was considered by Balas and Young (1995). It is a 18-bay truss structure equipped with accelerometers, displacement sensors, and torque wheel actuators. Feedback control can be implemented via a data-acquisition and control setup capable of operating at a sample rate of 80 Hz. A 28-mode model of the structure is available for analysis and simulation. The authors developed robust controllers for this structure based on a simplified 5-mode model, with deliberately introduced inaccuracies in the damping ratios and natural frequencies of these modes. No information about the higher-order modes was included in this representation. Despite the crude design model, the authors were able to use μ-synthesis to design controllers which used only a reduced set of the accelerometer measurements, no displacement measurements, and yet delivered very high performance levels. These designs were then verified, both in simulation, and experimentally on the structure. In contrast, H_∞ control designs for this model proved unstable on the more accurate model, and consequently were not experimentally implemented for the actual structure.

An example of application of μ-synthesis techniques to a civil engineering structure, a model of a three -story metal frame, Spencer et al (1997), may be found in Young and Bienkiewicz (1997). Here these techniques are applied to a benchmark problem in earthquake engineering. They were combined with a model reduction to yield a low-order robust controller for a fairly complex problem. In this case the experimental data is not currently available, but the resulting 4^{th} order controller performs well in simulation, and satisfies the appropriate robustness analysis tests.

6. PROSPECTS

Recent developments in structural control and successful implementations of control systems for mitigation of response of civil engineering structures suggest wider application of this technology in the near future. From perspective of wind engineering, especially encouraging and valuable are reports on performance of installed (active/hybrid) systems. As mentioned before, many designs of tall/long-span structures are governed by serviceability (occupant comfort) criteria. It appears that improvement in comfort of occupants of buildings and other wind-sensitive structures will remain for the near future the primary function of active systems designed to mitigate wind effects. Experience gained from technology developed for this purpose will be very useful in the design of the next generation of control systems, namely those targeting limit state/safety issues related to extreme winds and other natural and man-made phenomena.

Application of active control technology continues to receive a high level of attention in the earthquake engineering community. Actually, experience with control systems to mitigate earthquake effects has been applied in design of active devices to suppress wind-induced structural response. We anticipate that, as interest in response control among wind engineers increases, stronger ties will be established between earthquake and wind engineering researchers and practitioners involved in structural control. This may lead to an accelerated progress in structural control technology, with benefits to both groups. One of immediate steps in this direction could involve benchmark problems.

Wide response to a call for papers addressing two benchmark problems, Spencer et al. (1997), for active mitigation of earthquake effects is very encouraging. The issue of benchmark problems for structural control has been also identified by working groups of a recent workshop, Second International Workshop on Structural Control (1996). Two types of problems could be considered for control systems to mitigate wind effects: (1) Problems involving structural models selected also for studies of control of response due to earthquakes, and (2) Problems identified for testing structural control designs for wind effects. The second group might involve computer simulations coupled with wind tunnel studies of models of varied degree of fidelity. This leads to an issue of establishment of testbed facilities for laboratory (wind-tunnel) as well as full-scale testing.

The concept of testbed facility developed for the NASA Minimast facility might be used as a "blue print" for a full-scale testbed facility for active mitigation of wind effects. In fact, perhaps it would be possible to initially designate (on a temporary/trial basis) one of the exiting full-scale structural control research facilities, as a possible full-scale testbed site. Practical aspects and organizational issues could be identified and prioritized through a feasibility study and possibly a workshop initiated /organized by this panel and involving interested groups and individuals.

Implementation of the idea of testbed facilities, both for laboratory as well as field testing, is one of issues which are well suited for international collaboration. In particular, combination of practical experience resulting from development and operation of the installed control systems, expertise and perspective offered by wind engineering researchers and practitioners, and involvement of experts from control community in US, Japan, and possibly other countries, seems to be of great potential. The resulting synergy is expected to lead to major breakthroughs in a number of areas, including those identified earlier as critical issues.

Application and adaptation of techniques of robust control appear to offer unique opportunity for improving reliability, robustness, and performance of practical control systems for mitigation of wind effects on buildings and structures. The proposed activities might focus on control devices permanently integrated with a given structural system as well as temporary mechanisms, e.g. installed/used during construction, tentative retrofit, and under other circumstances.

7. CONCLUDING REMARKS

The outlook for wider application of control systems employing active components to mitigate wind-induced effects appears encouraging. Despite impressive progress in this area, more effort is needed to address a number of issues. Experience with practical and installed systems (in Japan) is very valuable. It seems clear that modern techniques and tools of robust optimal control have tremendous potential for the complex problems that arise in practice, in particular for civil engineering structures. Work is needed to evaluate which strategies perform best for a given class of structures and how to implement them in the most optimal manner.

It has been recognized that cross-disciplinary and international collaboration is the prerequisite for an accelerated progress in the area of structural control. It is proposed that the UJNR Panel on Wind and Seismic Effects considers research and development activities addressing systems with active control components to mitigate wind-induced response as one of high-priority topics.

Focus on devices targeting serviceability issues due to moderate winds seems to be timely and relevant. This case is very important, since such conditions occur quite frequently. An uncomfortable environment (e.g., in an office/hotel/residential skyscraper or other wind-sensitive structure) can adversely affect occupants and work productivity, and it may ultimately result in disruption in business cycle, and possible financial losses.

8. ACKNOWLEDGMENTS

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Table 1. Some Distinguishing Features of Structural Control of Civil Engineering Structures, Housner et al. (1994a)

	FEATURES
STRUCTURE	* Complex system with few critical modes * Exhibit nonlinear behavior
SENSING & ACTUATION	* Few sensors & actuators * Limited response variables for sensing * Large control forces with high speed
CONTROL OBJECTIVES	* Reduction of selected maximum response * Imprecision in control objectives
CONTROL STRATEGIES	* Simple but robust and fault tolerant control * Suboptimal control * Implementable control laws

Table 2. Signal Energies for Unperturbed Response

Unperturbed Response	$\frac{\|u\|_2}{\|w\|_2}$ $\left(\frac{\text{Control Effort Energy}}{\text{Disturbance Energy}}\right)$	$\frac{\|z\|_2}{\|w\|_2}$ $\left(\frac{\text{Output Acceleration Energy}}{\text{Disturbance Energy}}\right)$
Open-Loop	0	1.564×10^{-12}
$\mathcal{H}_2$	0.631	7.34×10^{-13}
$\mathcal{H}_\infty$	0.646	7.08×10^{-13}
μ-Synthesis	0.480	9.92×10^{-13}

Table 3. Signal Energies for Perturbed Response

Perturbed Response	$\frac{\|u\|_2}{\|w\|_2}$ $\left(\frac{\text{Control Effort Energy}}{\text{Disturbance Energy}}\right)$	$\frac{\|z\|_2}{\|w\|_2}$ $\left(\frac{\text{Output Acceleration Energy}}{\text{Disturbance Energy}}\right)$
Open-Loop	0	1.41×10^{-12}
$\mathcal{H}_2$	2.79	2.02×10^{-12}
$\mathcal{H}_\infty$	14.1	9.02×10^{-12}
μ-Synthesis	0.545	1.18×10^{-12}

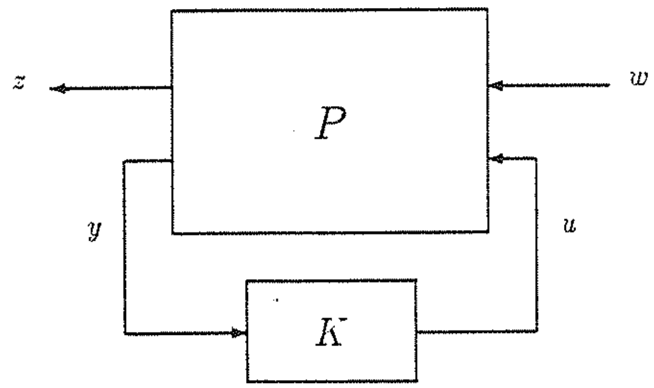

Figure 1. Canonical Form for Optimal Control

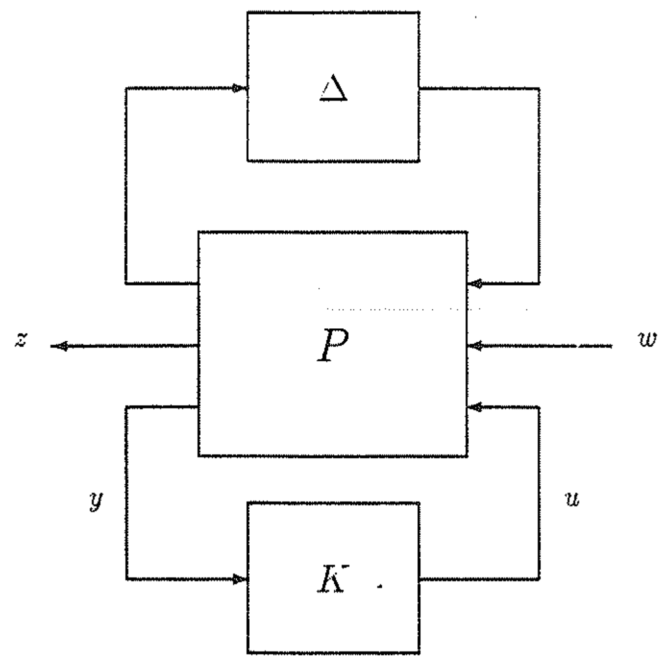

Figure 2. Canonical Form for Robust Control

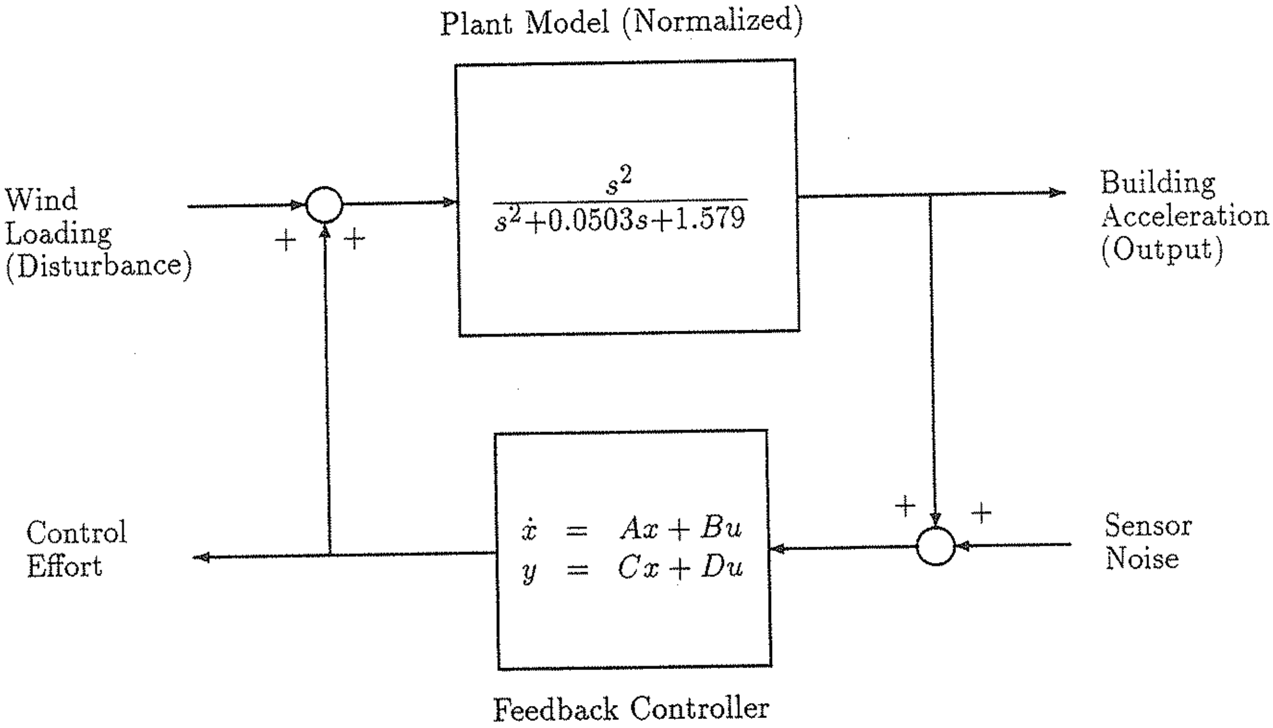

Figure 3. Structural Feedback Control

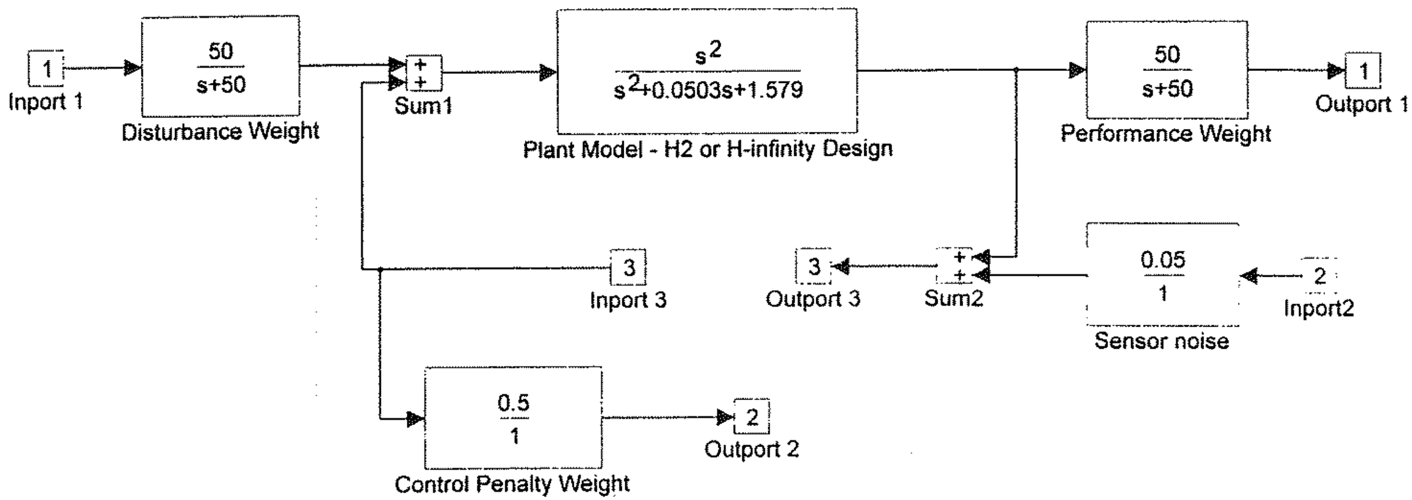

Figure 4. Optimal Control Design Model

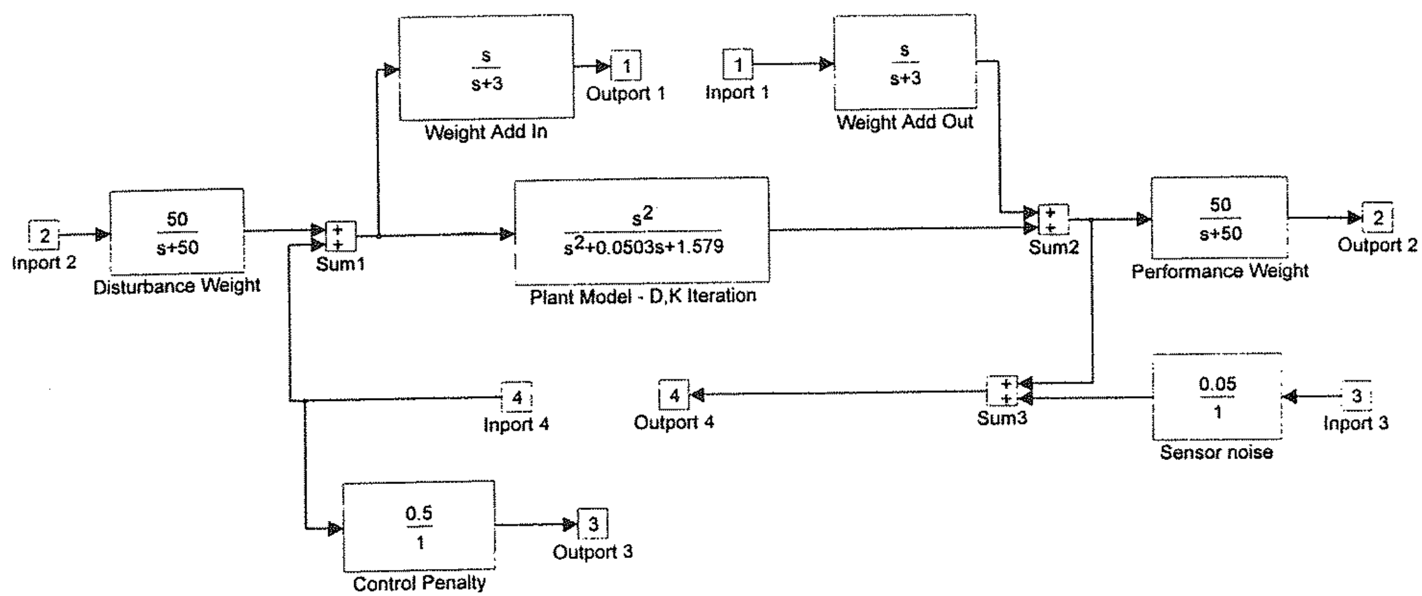

Figure 5. Robust Control Design Model

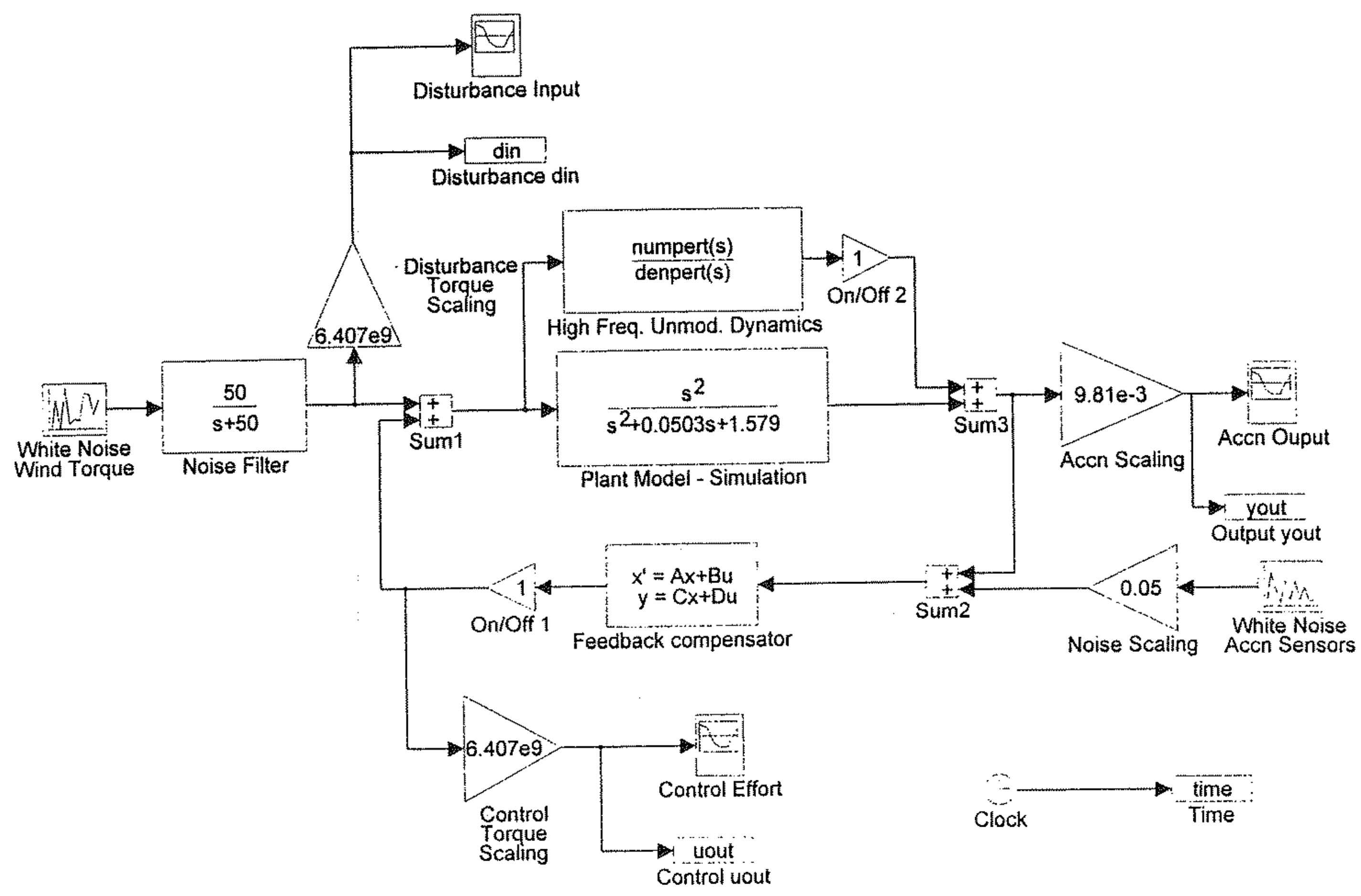

Figure 6. Simulation Model

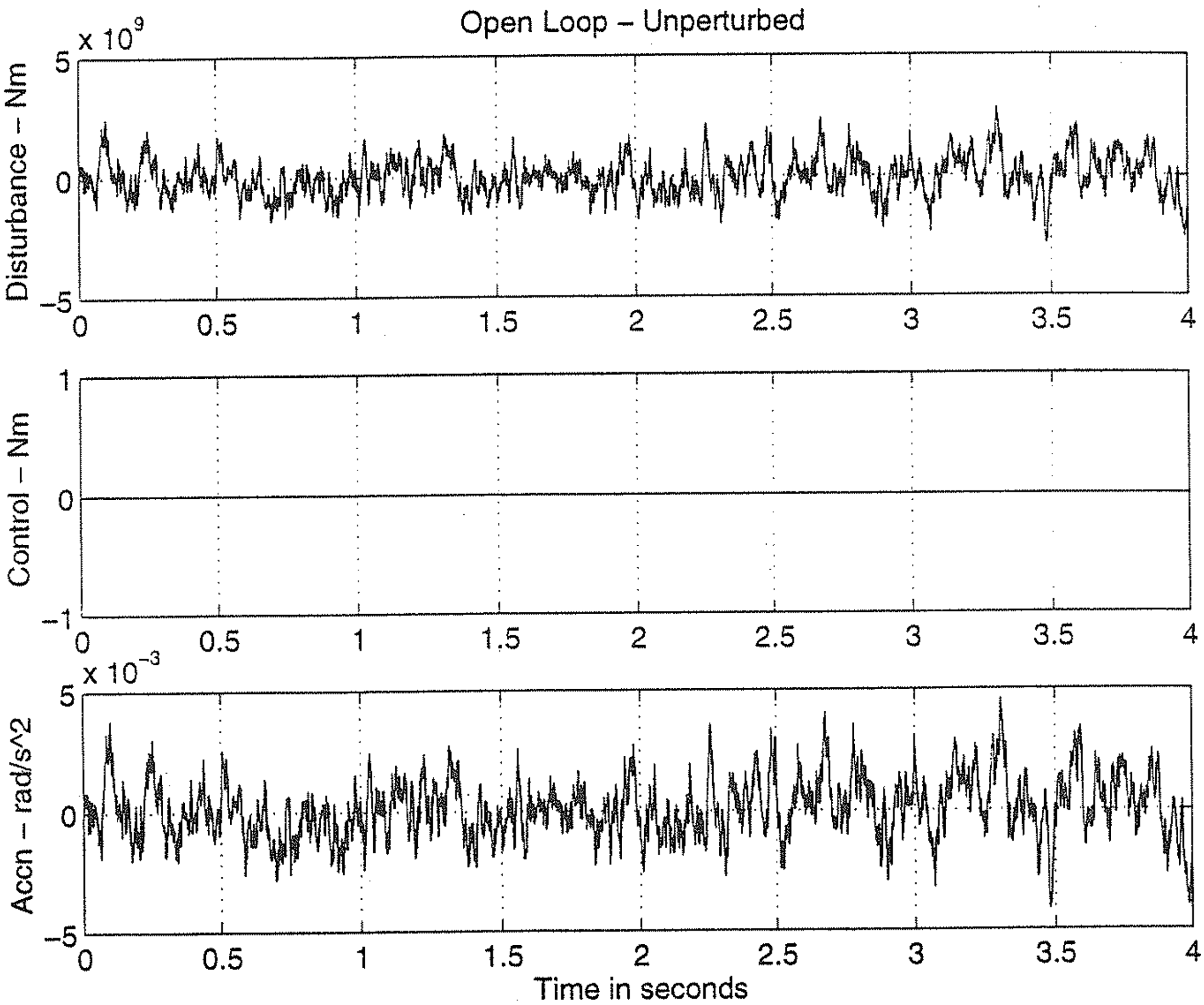

Figure 7. Unperturbed Open-Loop Response

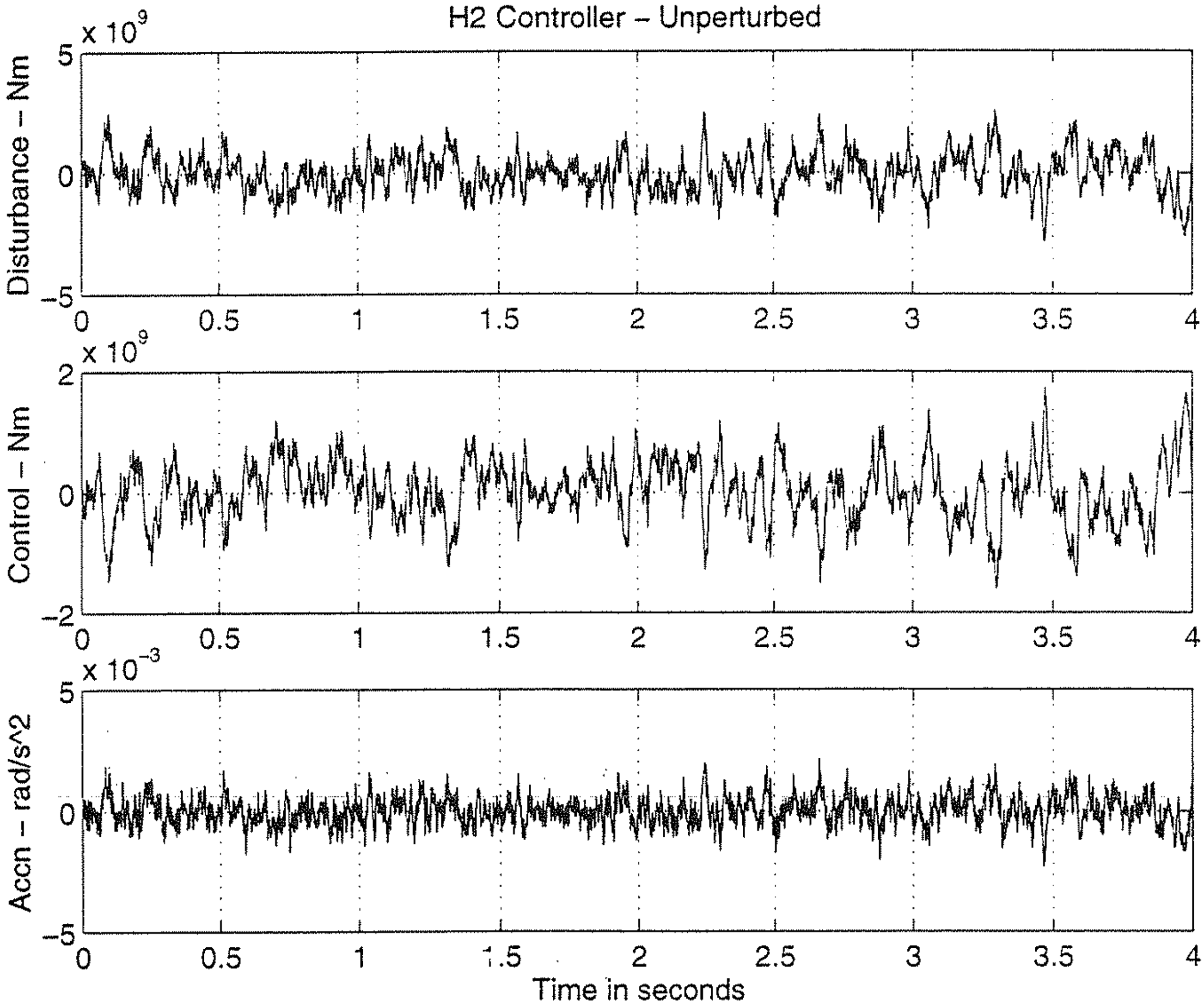

Figure 8. Unperturbed H_2 Control Response

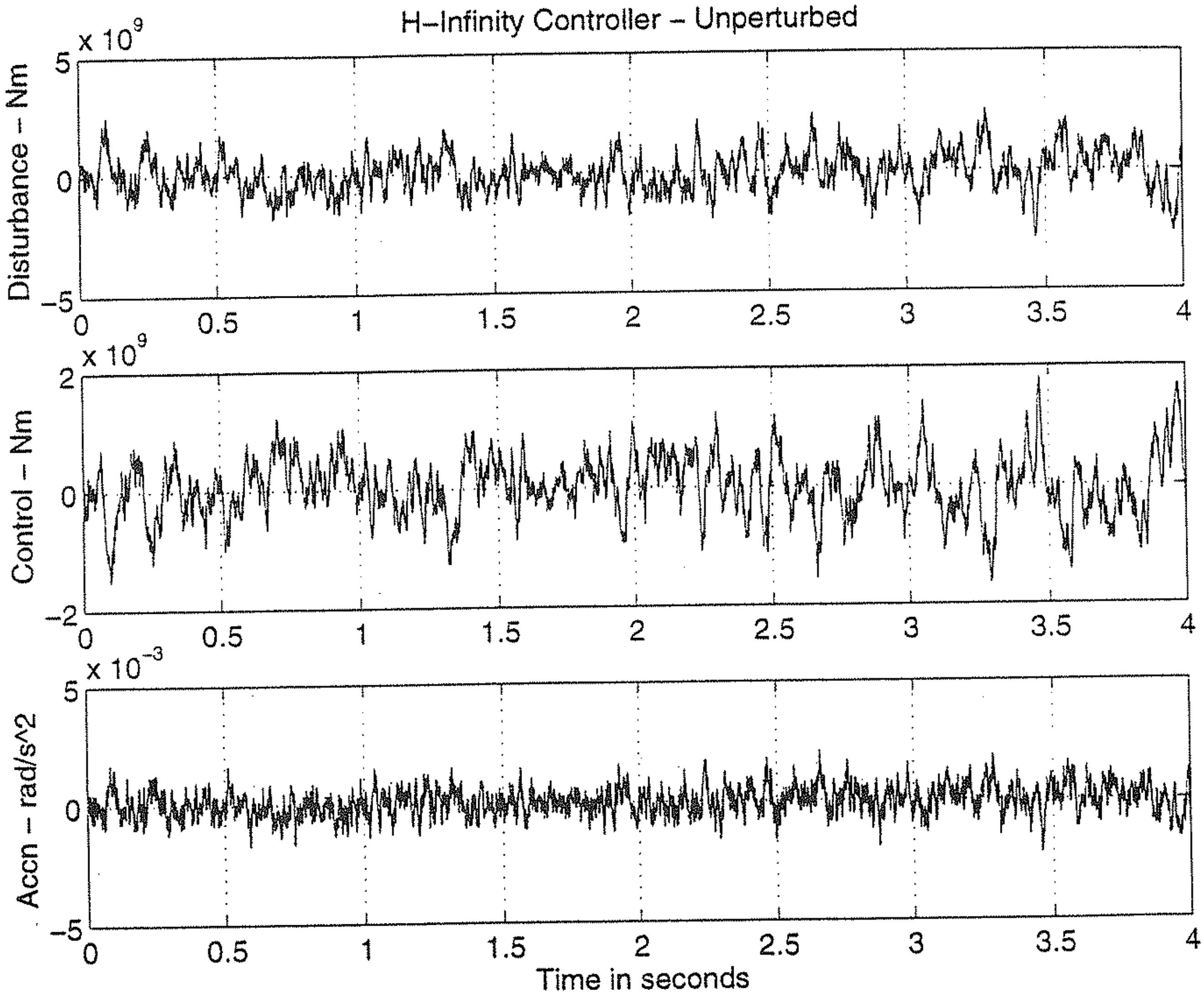

Figure 9. Unperturbed H_∞ Control Response

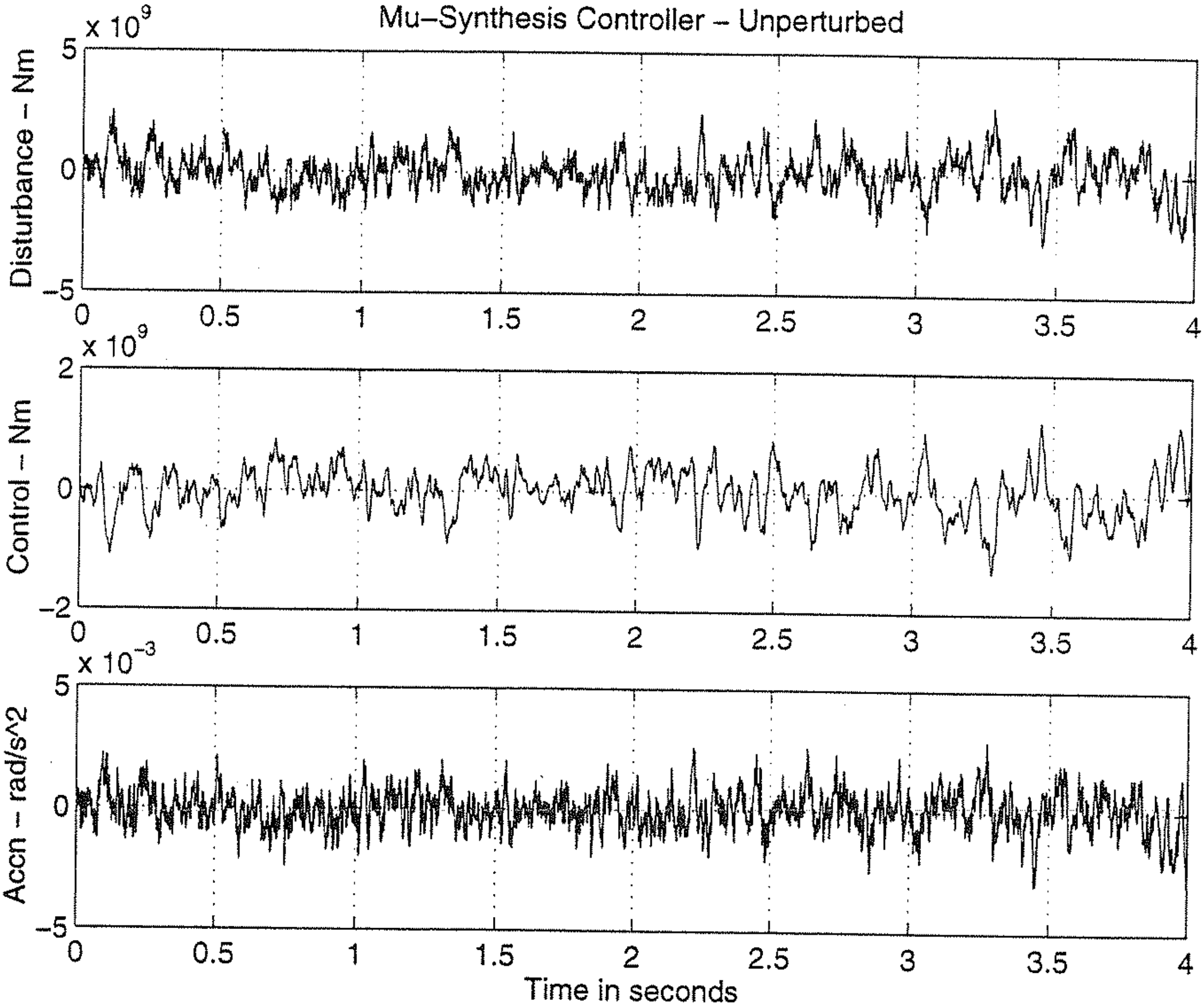

Figure 10. Unperturbed μ-Synthesis Control Response

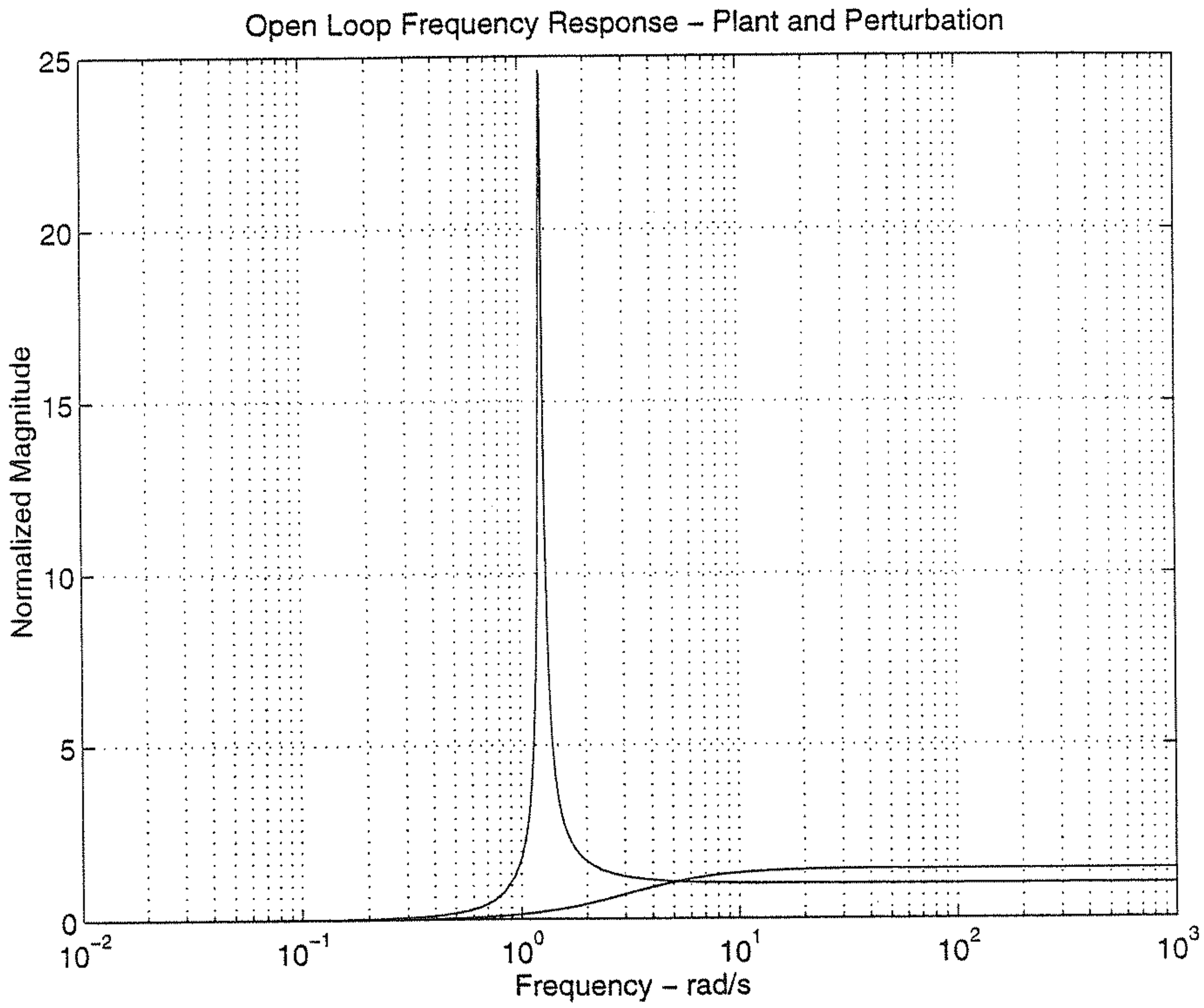

Figure 11. Frequency Response of Open-Loop Plant and Perturbation

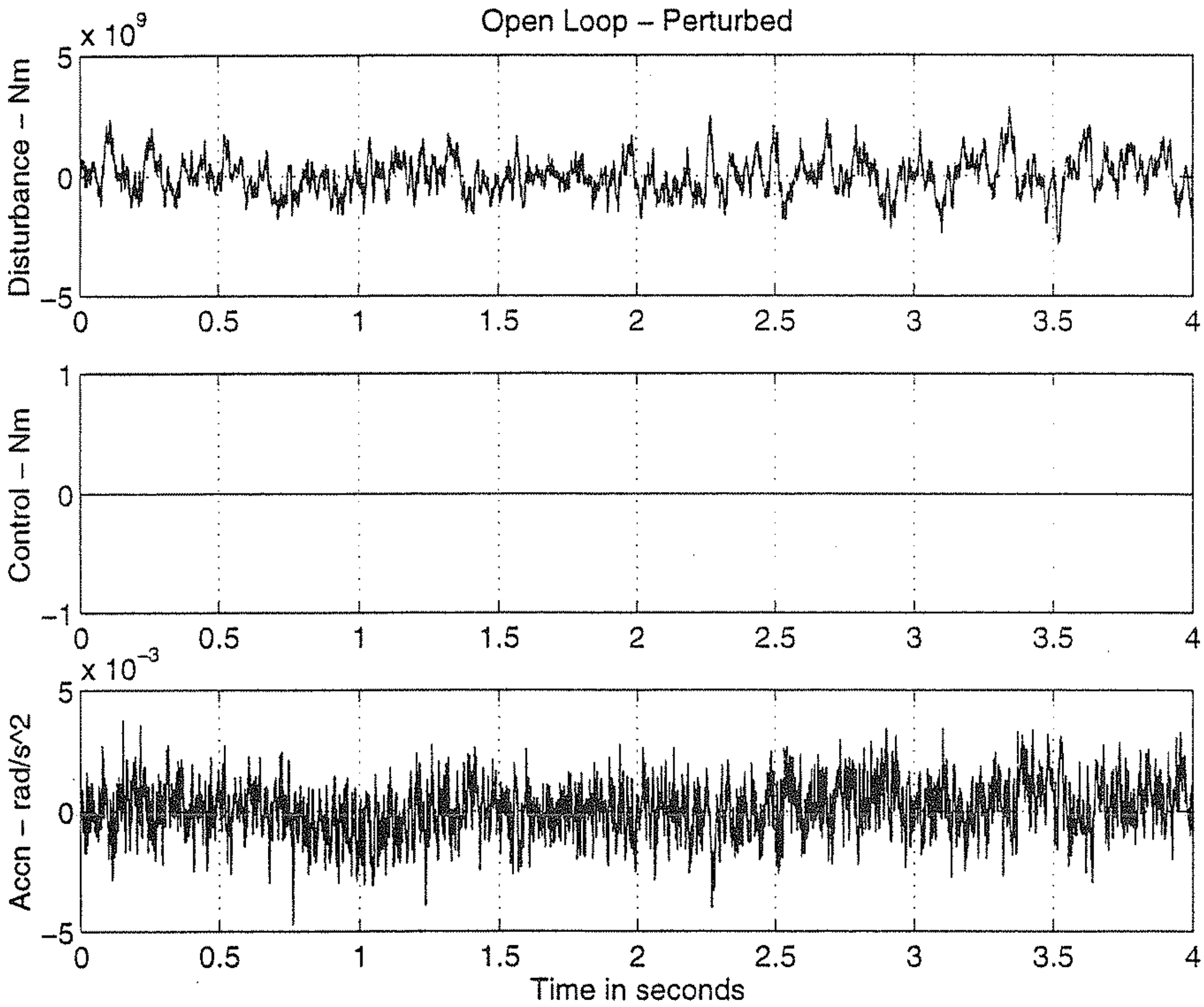

Figure 12. Perturbed Open-Loop Response

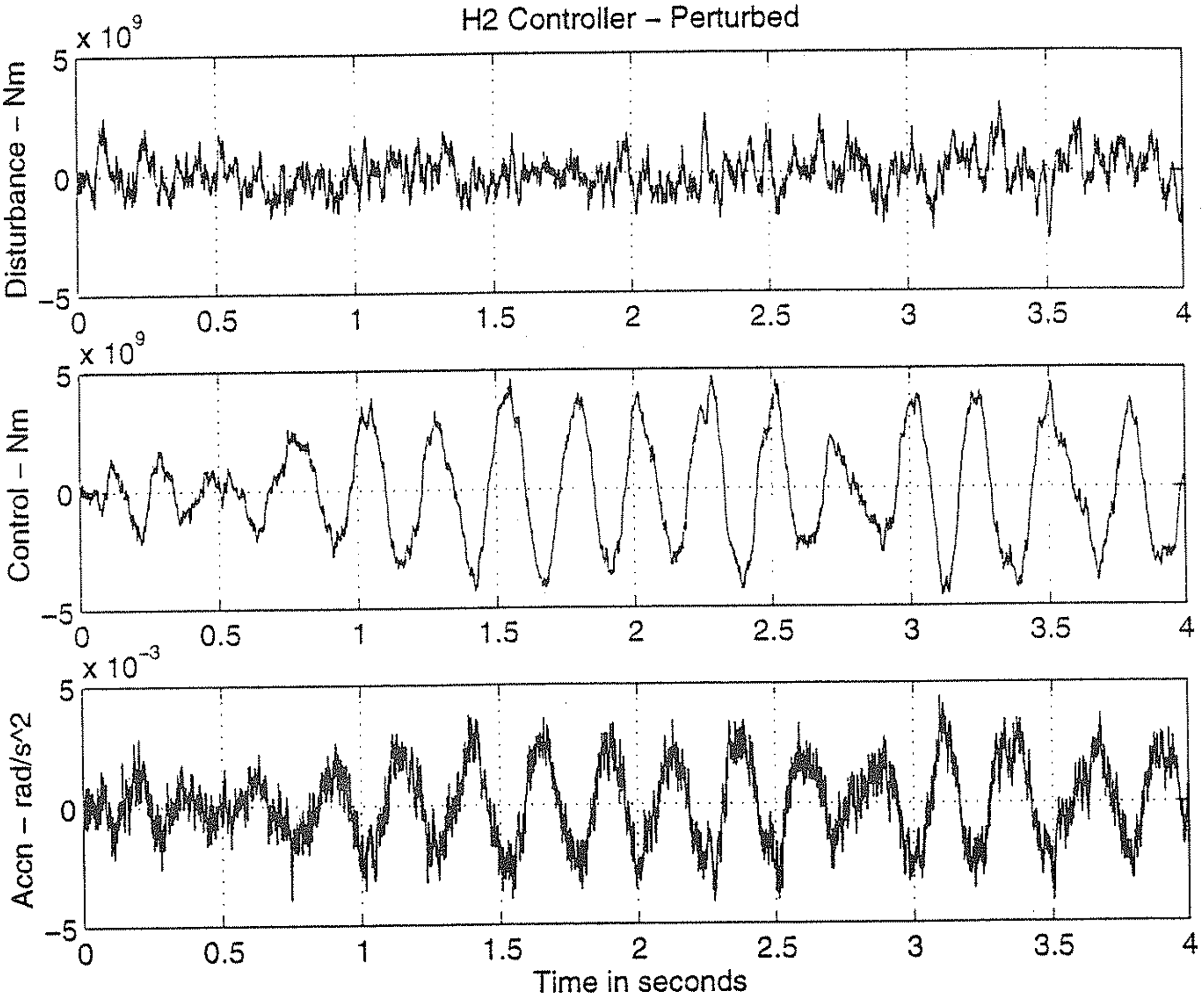

Figure 13. Perturbed H_2 Control Response

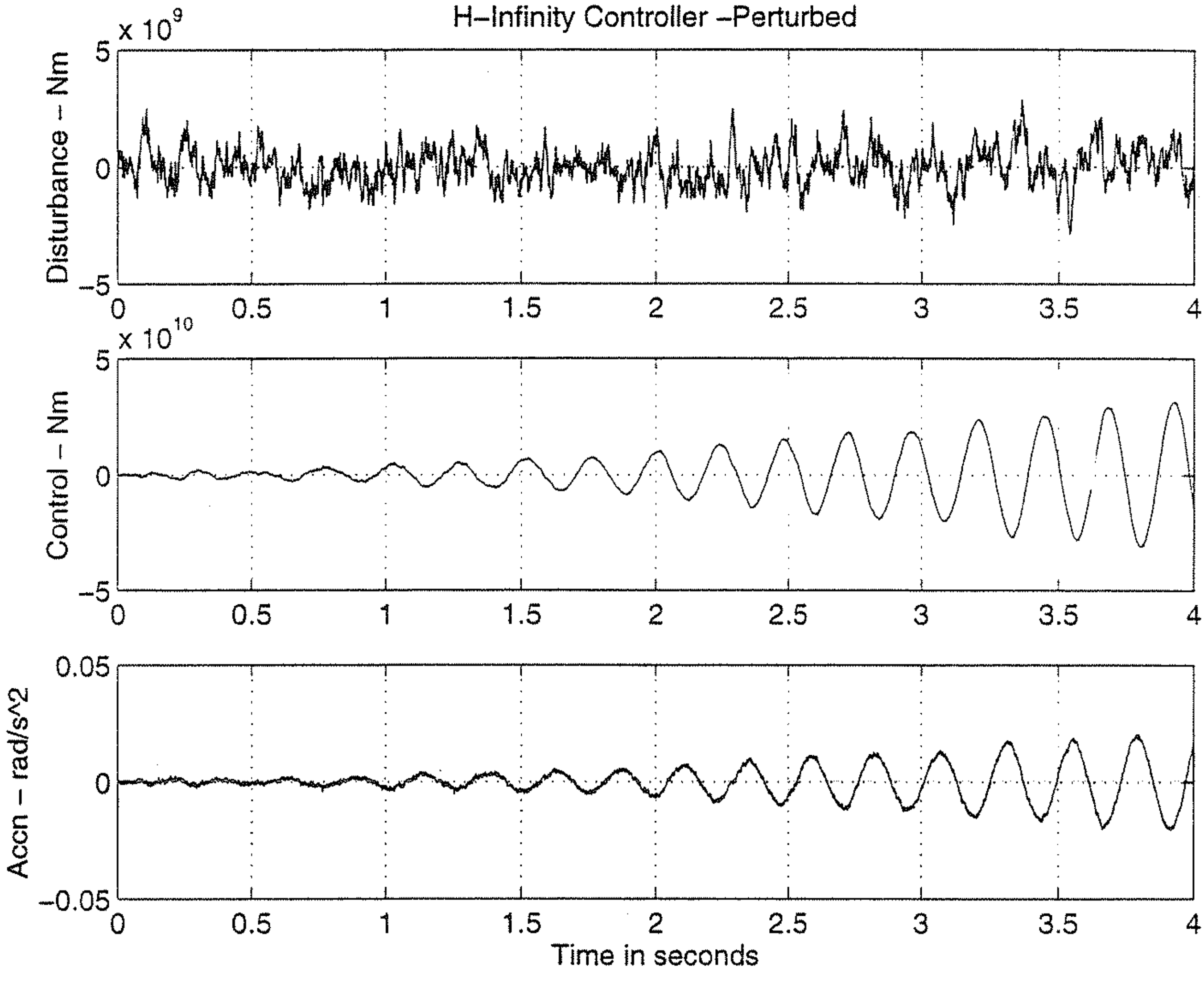

Figure 14. Perturbed H_∞ Control Response

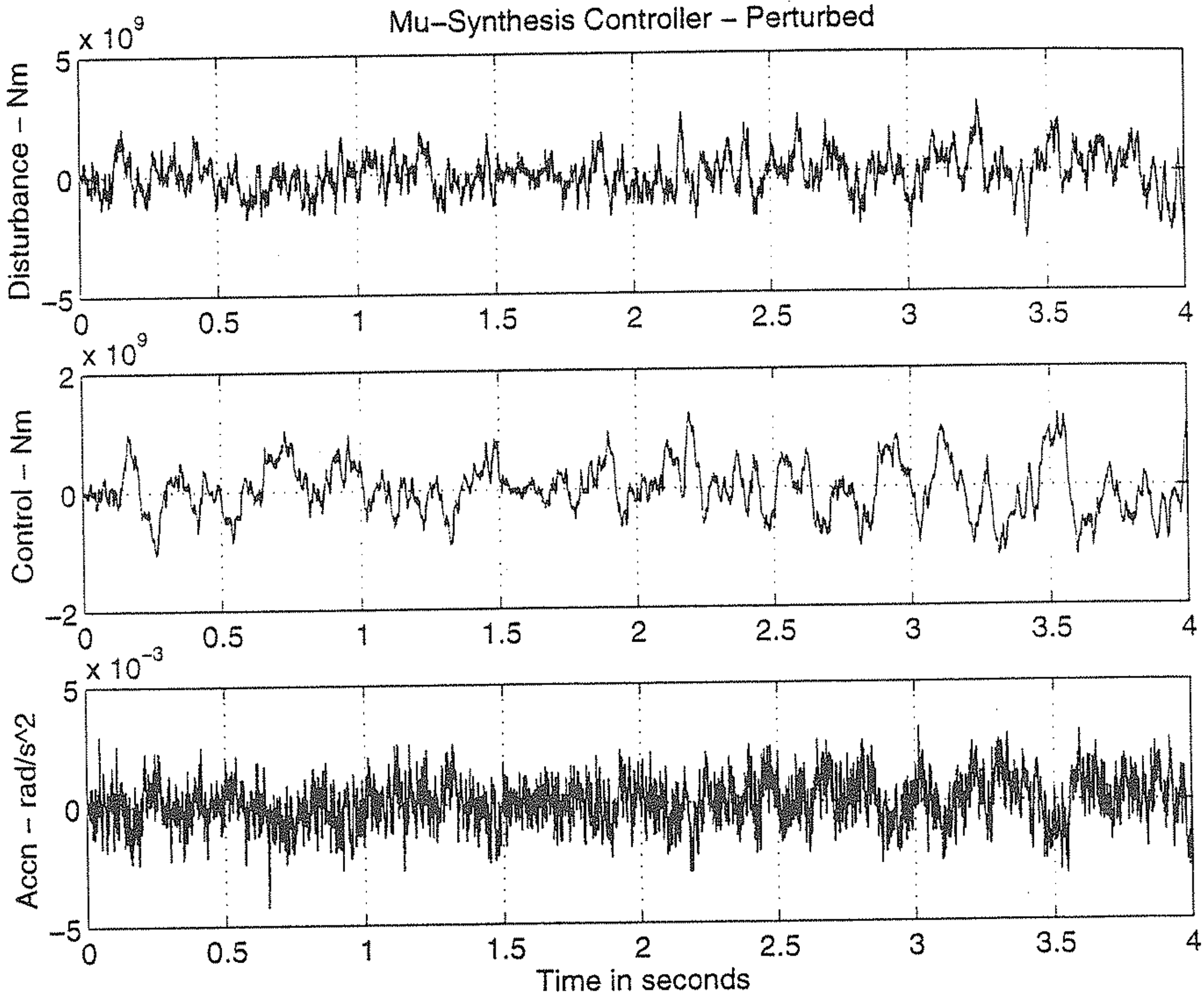

Figure 15. Perturbed μ-Synthesis Control Response