Chapter 9
Applications of Model Predictive Vibration Control

This chapter will briefly review some of the existing applications of model predictive control for vibration attenuation or its closely related fields. The application of model predictive control as a vibration reduction strategy is not common, and there are only a handful of available publications related to this field. The existing literature is mostly based on well-established, however slightly outdated theoretical findings such as GPC and DMC; see for example [27, 33, 78, 102, 154] and others. At this time the only available published work featuring model predictive vibration control *with system constraints* and online optimization is presented by Wills et al. in [142, 143], which has inspired the authors of this book to further investigate the topic and include stability constraints in [126–128, 125]. Since predictive control for active vibration attenuation especially with constraints and stability guarantees is a nearly non-existent field [10, 33], a further research of its properties and application possibilities is warranted.

Of course, as it was already noted in the preceding chapters, one may expect that systems and structures with multiple-inputs and multiple-outputs (MIMO) are especially suited for model predictive vibration control. Unlike in the case of simple single-input and single-output (SISO) systems, the advantages of MPC methods and the increased performance of vibration attenuation over other control approaches will be evident in more complex application scenarios, involving multi-point sensing and actuation. MPC controlled systems will always perform better than saturated strategies, as these controllers are either overly aggressive because they have been tuned without constraints in mind (potentially leading to unstable control course), or are too conservative because their performance is meant to reflect the saturation limits (not using the full potential of the closed-loop system).

In addition to reviewing suitable applications of MPC as a vibration reduction strategy, the properties and issues of the current implementations utilizing other control approaches are also discussed in this chapter. The few existing works on MPC or related vibration attenuation applications will be presented, along with a discussion of the application of model predictive vibration control in fields where so far only traditional industrial feedback control has been applied.

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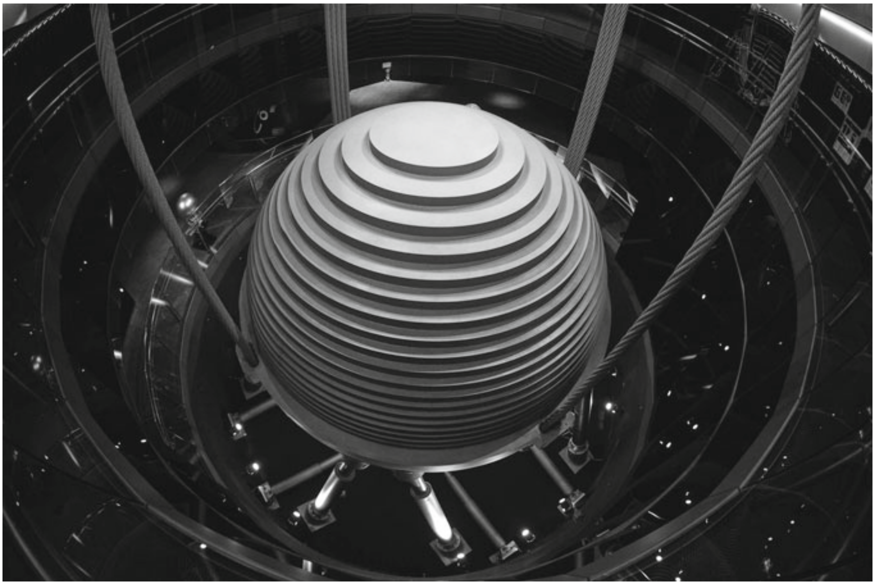


Fig. 9.1 The tuned mass damper on display in "Taipei 101" [22] is a prime example of the potential of both passive and active vibration control systems designed to save lives in civil engineering structures

We will begin the first chapter of Part III by presenting simple demonstration examples in Sect. 9.1: cantilever beams, plates, disks and other structures. These laboratory applications may seem elementary, but in many cases adequately emulate the dynamic behavior of more complicated real-life systems. Academic literature already lists a few successful applications of various MPC algorithms for the vibration damping of these structures, some of which we will discuss here. The following section examines current examples of vibration control in the field of robotic manipulators and other similar systems. Structural attenuation in optical systems is introduced in Sect. 9.3, while the difficult application scenario of active noise control is briefly reviewed afterward. The automotive industry driven by the desire to fulfill customer needs has always been keen on introducing innovations—including different forms of vibration attenuation and damping—in order to increase passenger comfort. The possible application fields of model predictive control in the transport industry are investigated in Sect. 9.5. Vibrations induced by earthquakes are especially dangerous to human life; therefore, any measure against its effects is extremely important. In addition to some of the already existing passive counter-measures, as the tuned mass damper of the Taipei 101 illustrated in Fig. 9.1, Sect. 9.6 prevalently deals with active or semi-active control systems in the field of civil engineering, which may benefit from the application of model predictive control. After a brief excursion into the world of vibration insulated platforms and machine tools, the chapter is finished by a section devoted to the aerospace industry and spaceflight.

9.1 Concept Demonstration Examples

The seemingly simple cantilever beam structure is at the focus of many research publications, as it can represent the basic dynamic behavior of a broad range of physical systems, such as wing surfaces in fixed and rotary wing aircraft, civil engineering structures, space structures and others. From the viewpoint of the control engineer, the dynamics of such a simple experimental laboratory structure fully emulate the problems encountered with real lightly damped structures such as fast dynamics, the need for constraints and others.

9.1.1 Cantilever Beams

The active vibration control of a cantilever beam using model predictive control has been considered by Kim and Washington in [48]. In this work, predictive control is only utilized to enhance the properties of sliding mode control. Generalized predictive control has been featured in [102] to suppress the vibrations of a piezoelectric patch-driven flexible clamped beam. The resultant GPC law is in a closed form without constraints. The authors compared GPC to positive position feedback, citing inconclusive performance advantages of GPC over PPF.

Adaptive GPC has been implemented for a piezoelectric device-driven cantilevered beam in [77] and later in [78]. The data acquisition of this system has been set at 200 Hz with the adaptive controller updates performed at third of the sampling rate. The adaptive feature certainly requires increased computational efforts; however, for an unconstrained predictive controller, such sampling speeds are not very impressive and severely limiting the effective bandwidth of the vibration attenuation system. In addition, the GPC approach may be considered slightly outdated by today's prevailing research trends. The lack of system constraints allows for stability guarantees, which are given in a more straightforward fashion than in constrained MPC, thus avoiding any problems with limited regions of attraction.

A model predictive controller more consistent with current research trends applied to the structural vibration control of an experimental active cantilever is presented by Wills et al. in [142] and later in [143]. Here a linear time-invariant state-space system is used to model the vibration dynamics of the cantilever. The need for system constraints is emphasized on the grounds of the always-present physical actuator limitations. The model utilized by Wills et al. is of a relatively high order; that is $n_x = 12$ states to cover 5 transversal vibration modes in the 0–500 Hz bandwidth. This implementation assumes system constraints, thus uses a QP-based optimization procedure in the online regime. Given the fairly large model and the QP algorithm, the work has demonstrated impressive sampling speeds up to 5 kHz with a $n_c = 12$ steps long horizon. The high sampling speeds have been reached by using a digital signal processor board with a customized active-set QP algorithm. The question of stability has been treated by using a dual-mode MPC algorithm; however, without the application of a constraint checking horizon to ensure the feasibility of the predicted input tail. Although this dual-mode concept is a big step up from the generic finite horizon MPC approach, it can still not guarantee stability a priori. The findings by Wills et al. confirm that constrained MPC outperforms a saturated (clipped) LQ controller in terms of vibration damping performance.

In previous works by the authors of this book a computationally efficient, suboptimal constrained MPC approach has been applied to damp cantilever beam vibrations in [128, 127], where stability guarantees have been given a priori. Later this suboptimal approach has been compared to multi-parametric MPC in [126], suggesting issues with the implementability of stabilized constrained MPC on lightly damped systems. The vibration damping performance and implementation properties of different MPC algorithms with constraints and guaranteed stability have been analyzed as well. Based on this, the application of constrained stabilized MPC to lightly damped vibrating structures will be introduced in detail in the upcoming chapters.

The active vibration control of simple cantilevered beams through various control strategies other than MPC is discussed in numerous publications. A neural-networks approach is used in [46], fuzzy control is utilized in [66, 140], genetic algorithms are used for actuator placement and feedback gain optimization in [105, 148]. Electrorheological fluid-based mounts are used to damp a cantilever semi-actively in [43]. Several other works examine the different aspects of clamped cantilever beam vibrations [76, 133].

9.1.2 Plates and Shells

Another article considering an adaptive-predictive control approach based on the GPC controller concept is aimed at suppressing plate vibrations [27]. Similarly to the previously introduced works, Eure applied a finite horizon predictive controller without stability guarantees. The adaptive GPC controller has been able to cover a bandwidth of several kHz with corresponding high order models, which would been very difficult to perform with a quadratic optimization-based constrained MPC algorithm.

The vibration control of plates and shells, especially cantilever plates is also a highly researched topic. Some of the works focusing on the topic are for example [20, 98, 101]. Robust vibration control of circular shaped plates is investigated in [38].

9.1.3 Others

A less traditional active vibration control demonstration device is used by VandenBroeck at al. in [135, 136]. The authors utilize a two degree of freedom mass-spring-damper system and apply a novel time optimal MPC approach to this system.

The two DOF system is actuated by a hydraulic piston. The time optimal MPC approach of VandenBroeck steers the system into equilibrium in the shortest possible time [135], without concentrating on the effort of minimizing the cost function. This novel and alternative interpretation of the MPC law can be beneficial for other vibrating systems as well.

9.2 Manipulators in Robotics

The increasing efficiency of robots and manipulators demands the constant increase of operational speeds while at the same time due to cost effectiveness and weight optimization the manipulating arms become increasingly flexible. Due to the increased flexibility, the vibrational response of such systems cannot be ignored anymore. Lightweight manipulators are of special interest for spacecraft.

Model predictive control of a flexible link manipulator mechanism is often investigated in the literature. The problem is recurring and is not strictly limited to manipulators, as these mechanisms have the same generic dynamical behavior as other lightly damped structures, such as solar panels, antenna systems, truss structures in space or for that matter simple cantilever beams. Even though the majority of works dealing with manipulators do not explicitly focus on vibration issues, some do allow for the attenuation of vibration dynamics or at least consider the possibility to use an MPC controller for this purpose.

Unconstrained predictive vibration control of elastic manipulators appears as early as 1996 in [151] by Yim. The author uses an unconstrained formulation of the predictive control law with a slightly modified quadratic cost function to arrive at a closed control law. The stability of the system is investigated by inspecting pole locations of the resulting closed-loop system.

An unconstrained MPC method has been applied to the control of vibrations of a flexible link manipulator in [157] by Zmeu and Shipitko. The closed form of the controller utilized a model based on an offline artificial neural network learning process. The work did not treat the stability of the system explicitly.

A multivariable model predictive control based vibration reduction system for a flexible link mechanism has been introduced in [33]. Much like other available publications considering predictive vibration control, Hassan et al. assumes a predictive controller based on early formulations such as FIR- or FSR-based methods. Constraints or stability issues have not been explicitly treated in this work either.

Boscariol et al. considered a constrained MPC control of a flexible link manipulator in [10] and compared control performance to more traditional approaches. The work is aimed both at position and vibration control and utilizes a linearized state-space model of the dynamics. Even though the robustness of the controller is discussed and tested in simulation by introducing uncertainties, a priori stability guarantees are not ensured in this work, neither is the question of stability thoroughly discussed. An unstable MPC controlled manipulator arm may pose serious issues in many critical applications: both the vibration control and the position control of the arm may go out of hand, and risk mission objectives and possibly even human life.

The vibration control of flexible link manipulators is discussed, for example, in [44, 67, 106, 121, 144] with control strategies other than MPC.

9.3 Optical Systems

The vibration control of optical systems enhances image quality that is deteriorated due to the vibration of the optical system or its components. A well-known example of optical image stabilizers can be found in high-end photography equipment such as camera bodies and lenses.

The other good example of vibration control systems in optics is telescopes in astronomy. It is very difficult to cast mirrors larger than 7 m in diameter from a single piece of glass, therefore future reflectors shall be constructed from an array of optical systems [62, 99]. The problem with such a multi-mirror setup is that the positioning of the individual elements has to be precise enough to mimic the properties of a monolithic mirror even in the presence of outside disturbances. Moreover, in ground-based astronomical observatories the source of disturbance of the images come not only from mechanical sources, but the mirrors are significantly affected by atmospheric conditions as well.

The application of MPC in the vibration control of optical systems is manyfold and the need for actuator constraints is important in this situation as well. Unlike with the lightly damped systems presented before, the actuator and disturbance asymmetry is small in optics, therefore the need of long horizon MPC to ensure a proper sized region of attraction is not likely. The implementation potential of constrained MPC with stability guarantees as a vibration reduction technique in optics is high and only limited by the bandwidth of the disturbance and computational efficiency of the algorithm, and not the region of attraction.

Optical jitter has been attenuated experimentally by a real-time implementation of an adaptive GPC algorithm in [78]. The sampling rate has been set at 600 Hz citing that the jitter occurs at half this frequency. While it is questionable whether a sampling speed which is the double of the upper bandwidth is satisfactory enough, an unconstrained predictive controller could surely do better than this speed.

Model predictive control has been suggested to control the vibrations of rear-view mirrors in luxury or heavy vehicles by Larchez in [58]. The image quality of rear-view mirrors affects driver comfort due to increased eyestrain and blurred images may cause a road safety hazard as well. Disturbances contributing in increased blurriness due to vibration are limited to the 5–200 Hz frequency range. The need for predictive control has been justified because of the delays in the hardware loop. Larchez utilized a type of a simple adaptive-predictive controller, based on the filtered-x least mean square approach. The work demonstrated a significant vibration attenuation capability in experimental tests, nevertheless lacked system constraints. Even though the sampling frequencies were relatively high, there was no need to use long prediction horizons since neither stability, nor feasibility guarantees have been given. From the control engineering viewpoint, the lack of system constraints removes most of the implementation difficulties. Because real actuators are always constrained by saturation, this kind of approach also introduces questions on the stability or the real optimality of the algorithm. To be fair, a simpler algorithm requires simpler and cheaper hardware, which is essential in the cost sensitive automotive industry. In this setting, the theoretical questions of stability or optimality are irrelevant as an actively attenuated rear-view mirror can pose a significant image improvement, and thus a competitive advantage over a conventional one.

The majority of works in active vibration control of optical systems utilize feed-forward approaches such as digital filters. A digital filter-based system has been introduced in [90] to correct the tracking error in automotive DVD drives due to road vibrations, while sliding mode control is used in [155] for a similar task. Another field of application for AVC in optics is the stabilization and tracking control of scanning probes in atomic force microscopes [18, 23]. An active vibration control system for an airplane mounted optical bench effectively attenuating sub 0.1 Hz frequencies is presented in [92]. Other works concerned with AVC in optical systems are, for example, [15, 62, 71, 86].

9.4 Active Noise Control

Active noise control (ANC) is a closely related field to active vibration control and it is concerned with attenuating sound waves. Sound is a pressure wave which may be actively attenuated by structure-integrated actuators or noise-cancellation speakers.

From the viewpoint of model predictive control, ANC is a field where the practical implementation of predictive controllers is very difficult. This is caused by the high frequency and wide bandwidth excitation that is usually encountered in acoustics. Audible sound is limited to frequencies between 20 Hz and 20 kHz. The sampling of the MPC algorithm covering acoustic frequencies has to exceed the highest expected frequency by approximately ten times. The implementation of a constrained MPC controller with online QP optimization in the range of the upper limits of the human hearing is burdensome with currently available hardware. However, an unconstrained controller is more likely especially if the disturbance is only limited to narrow bandwidths, thus requiring small model orders.

The situation is somewhat relieved by the fact that the sound energy of acoustic disturbance is unlikely to exceed actuator capabilities. Unlike in the case of lightly damped structures, a constrained MPC controller with stability guarantees does not require excessive horizons to ensure a region of attraction (a feasible set of states) covering all conceivable disturbances.

Adaptive dynamic matrix control, an older form of model predictive control based on the finite step response of the controlled system is utilized in [154]. As with other publications using simple predictive control formulations, Zhang and Gal did not consider the inclusion of system constraints into their formulation. The approach utilized in [154] seems to be both practical and as the results show functional, however not up-to-date with the modern findings of model predictive control theory such as constraint inclusion, state-space models or stability and feasibility guarantees.

The adaptive GPC predictive control strategy has been utilized in [77, 78] to minimize sound pressure in a closed experimental noise control test bed. Compared with the unattenuated system, the adaptive GPC algorithm was effective up to approximately 200 Hz. This has been reached by the implementation of a predictive controller without system constraints, essentially avoiding the usual implementation issues related with sampling speeds in MPC.

One of the applications where noise is not merely a comfort factor is submarines, where increased noise levels may cause the detection and elimination of the vessel by the enemy. Piezoelectric stack actuators configured counter phase in a T-shaped active stiffener have been considered in [91] and subsequently in [92]. The control strategy used in these works is not MPC based; rather it is founded on the equation of motion of the hull at the stiffeners, where the control moment is essentially calculated from minimizing the undesired deflections or pressures. While both displacement and radiated pressure minimization is considered in numerical examples with 40–90% noise level reduction [92], the inclusion of a state-space model-based MPC control approach could be certainly beneficial. The calculated resonant modes are located at 12, 24 and 35 Hz [91], therefore the real-time application of a MPC controller is feasible. Although the displacement effect of the piezoelectric actuators is still somewhat smaller than the expected deformations of a large submarine hull, the region of attraction in stabilized and feasible MPC is not a similarly serious issue as it is with cantilever beam-like structures. This in practice means the use of shorter horizons and the possibility to apply a broader range of MPC algorithms.

There are several works investigating the active control of acoustic noise using various traditional feedback control strategies. Active noise control in acoustic cavities such as trains or aircraft fuselages is presented using positive position feedback control techniques in [17]. A distributed control approach has been chosen in [35] to drive piezoelectric actuators anti-phase to minimize sound radiation. The positioning of control sources in three-dimensional noise control settings is discussed in detail in [56]. Li et al. performed a simulation study investigating active noise control of a medical MRI scanner in [63]. There is a wide selection of available publications discussing active noise control using different traditional control strategies, for example [12, 49, 54, 60].

9.5 Automotive Industry

Because the suspension transfers the force between the vehicle body and the road, a well-designed active suspension may enhance driving comfort, handling, vehicle service time and road safety. For commercial heavy vehicles, the aim of active or semi-active suspensions is to lessen dynamic tire forces to protect road surfaces and to protect cargo integrity. These objectives can be effectively met by the use

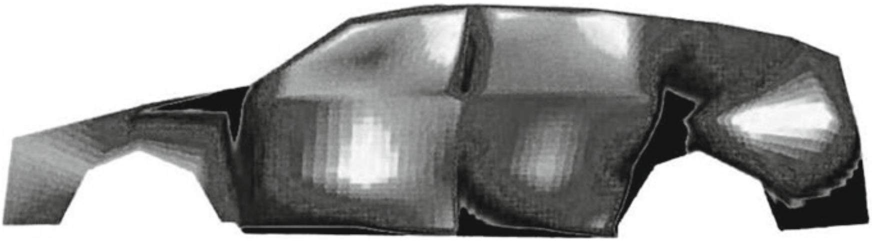


Fig. 9.2 Body vibration of a passenger car due to road excitation, measured by FKFS, Stuttgart, Germany [34]. The *darker* shades denote less vibration, while the *lighter* shades found mostly at the center of large panels indicate increased vibration levels

of MPC [75]. The body vibration of a passenger car resulting from typical road excitation is illustrated in Fig. 9.2, where the darker shades indicate lower vibration levels, corresponding to the stiffer areas of the body. The higher vibration levels are indicated by the lighter shades, those tend to be the areas inside large panels and surfaces.

Vehicle suspension systems essentially consist of a fixing mechanism (usually a wishbone or similar), a spring and a damper. This damper may be exchanged to a semi-active device, which provides a variable damping force based on the decisions of some control algorithm and feedback measurements. The (semi-)active dampers provide the variable damping force based on viscosity change as in MR dampers, or through a variable orifice valve, which can set the fluid flow conditions inside the damper. Model predictive control-based "preview" enhanced semi-active suspensions have been already considered for the HMMWV military vehicle [75].

A modified constrained model predictive control algorithm is proposed to control switching shock absorbers on a trailer semi-truck in [51]. The controller applied by Kok et al. is not predictive in a classical sense; however, it preserves most of its characteristic properties. The predictions in this work are generated by the observed disturbances measured at the front axle, while the control inputs are applied on the rear axle of the semi-truck—referred to as a control preview. In spite of a relatively powerful hardware configuration for the time, the real-time experimental implementation of this system was not feasible. A similar approach is featured in simulation in [75], where the optimization horizon was 16 steps with a 100 Hz sampling. Neither of the aforementioned works treated the question of stability arising from the nonlinear control law.

The MPC-based controller design for an electromagnetic motor-driven suspension actuator is presented in [39]. The controller is responsible for supplying current to the coil of the electromagnet and thus ensuring a given position. The constraints arise from both the available current limits (input) and the useful working space as well (output). A sampling speed of 100 Hz has been used with a relatively long $n_c = 40$ steps prediction horizon, given a system with three states. These parameters are within the limits of feasible implementation on current hardware, using generic QP algorithms. The work arrives at the conclusion that vibration damping capability of the constrained MPC system exceeding saturated LQ. Stability of the constrained MPC control law is not treated by Huang and Zhang.

The difficulty in designing a semi-active suspension is the hysteretic nonlinear behavior of MR dampers. Some authors employ soft-computing techniques such as neural networks to overcome this difficulty [152]. Other authors utilized a hybrid fuzzy—sliding mode controller for an ER-based automotive suspension system [124]. Classical feedback and various feedforward control-based semi-active and active vehicle suspension systems are discussed by many works, for example [26, 29, 74, 150, 152].

Other vibration control applications closely related to the automotive industry are for example the active vibration damping of seat suspension systems [123], to increase ride comfort and eliminate certain health concerns. The controller applied by Sun et al. is a $\mathscr{H}_\infty$ with a finite frequency response. The bandwidth of the controller is tuned to human comfort, around 4–8 Hz or the resonant range of internal organs. Sun et al. discusses the need to adjust for finite actuator stroke, therefore both the implied discrete sampling frequency and the requirement for constraints suggests the use of model predictive control for the vibration control of active seating systems.

Semi-active engine suspensions based on squeeze-mode ER fluid actuators are suggested in [141], while an electromagnetic inertia-mass actuator is utilized in [9] for the same task. A review of active vibration and noise canceling techniques is given in an earlier work by Shoureshi and Knurek in [109] and later in [110]. Since the advent of cheap microcontrollers, a wide spectrum of publications have appeared on the active vibration control and noise suppression in the automotive industry including works such as [41, 52, 122] and others.

In addition to the automotive industry, the vibration control of railway cars is considered by Kozek et al., where a heavy metro railway car is actuated by piezo stack actuators [53]. The combined artificial neural network and PI controller-based vibration control of magnetic levitation (MAGLEV) trains is investigated in [149].

9.6 Civil Engineering

Active control technologies are valuable as they may save human life and financial property during earthquakes. The integrity of civil engineering structures such as high-rise buildings, bridges, towers and infrastructure is not only jeopardized by seismic activity but by wind as well. Aerodynamic forces may induce vibrations similar to the case of wing flutter in aviation and severely disturb or destroy structures. The case of the infamous Tacoma Narrows Bridge collapse[1] still remains as a cautionary tale on the power of mechanical vibrations [7]. In addition to optimizing the structural design of buildings in areas of high seismic activity, passive means of damping are often employed, such as tuned mass dampers (See Figs. 9.1 and 9.5 for an illustration.), lead rubber bearings, friction pendulum bearings and others.

[1] See the Fig. 1.2 on p. 3 for an illustration.

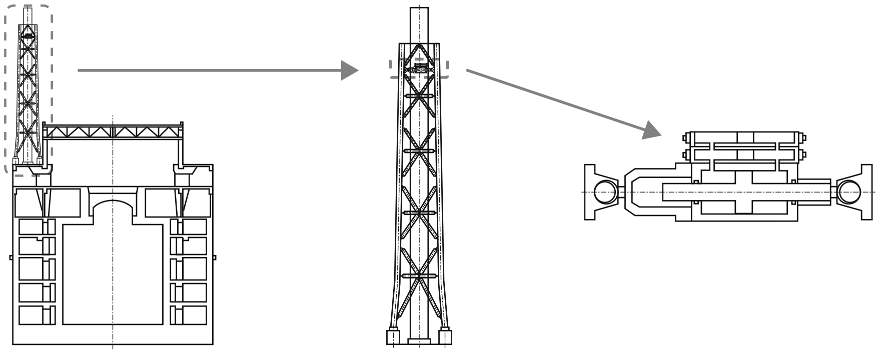


Fig. 9.3 A passive vibration control device is implemented at a stack of the Kashiwazaki Kariwa Nuclear Power Station located at a seismically sensitive area of Japan [146]. The image shows the cross-section of the reactor buildings, a detail of the stack and the passive vibration isolation device

In addition to passive technologies, semi-active and active seismic isolation systems have started to appear both in academic studies and in real buildings as well.

Although the major nuclear disaster at the Fukushima Daiichi power plant following the $M_w = 9.0$ magnitude [134] Tōhoku earthquake has not been the direct result of vibration phenomena but rather of equipment failure due to the tsunami wave [129, 145], engineers and safety experts are pushed even more to implement additional safety measures. The reactor buildings withstood the earthquake with an acceleration magnitude somewhat above their design limit, but the critical external power supply infrastructure that could potentially power the cooling equipment of the reactors was destroyed [107]. Figure 9.3[2] illustrates the passive seismic control system implemented for a stack of the reactor buildings six and seven at the Kashiwazaki Kariwa Nuclear Power Station in Japan [146], prior to the more recent Tōhoku earthquake. Because this power station has been previously affected by an earthquake in 2007, vibration insulation systems are steadily implemented as a way to enhance the seismic safety of this highly sensitive building. Active systems can improve on seismic safety even further; however, precautions must be made to ensure closed-loop stability.

In addition to input constraints arising from the physical limits of actuators, another set of constraints may be essential for an earthquake prevention technology. Output constraints in a form of maximal horizontal deflections in the building directly relate to the preservation of structural integrity. Model predictive control could be effectively used to incorporate these needs into the control law, while stability guarantees are also essential in this application field [50, 103]. As a potentially unstable controller may render the controlled plant unstable in the presence of a disturbance, so could an unstable control algorithm make the effects of a minor earthquake even worse by exciting the building into its resonance. This is mostly true for

[2] Courtesy of the Japan Society of Maintenology.

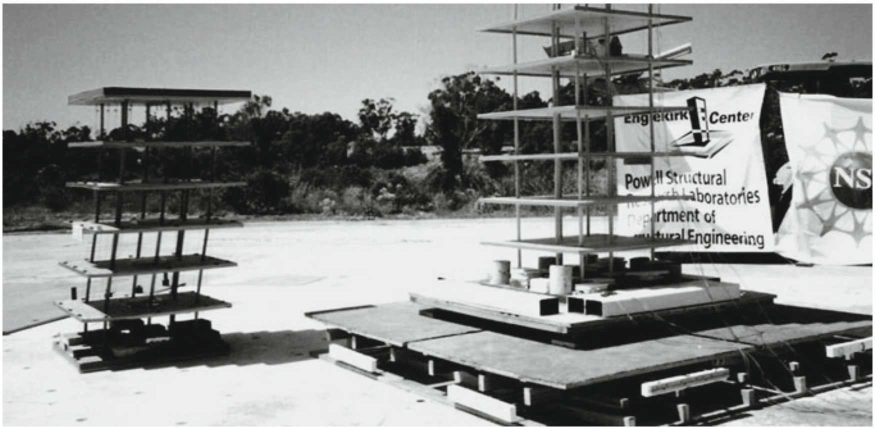


Fig. 9.4 Building models on a shake table at the testing facility of the University of California, San Diego. The *left* building is fixed directly to the table surface, while the one on the *right* is equipped with passive vibration insulation [111]

earthquake systems with active actuators. Since the physical effect of an actuator used in earthquake vibration control is small compared to the expected disturbance, an MPC controller with guaranteed stability utilized in such an application could possibly require a very large region of attraction. This actuator-disturbance asymmetry suggests implementation problems, which are similar to the case presented in the following chapters.

A semi-active magnetorheological damper-enabled earthquake control system is suggested in [147]. The response of the simulated high-rise building is nonlinear, however for design purposes Yan et al. considered linear MPC. The MPC control law featured in this work is unconstrained and has been expressed in its closed form. The authors debate the inherent stability of this system; however, this is not due to the controller design. On the contrary, even if the stability of an unconstrained MPC law could be expressed, here it is implied by the use of MR dampers that cannot add energy to the system, thus cannot render it unstable. This is up to debate, as the control system and even a badly designed passive system can still indirectly alter the resonant frequencies of a structure and shifting them closer to disturbance. The performance advantage of the closed form MPC law in comparison with LQ and saturated LQ was inconclusive, as different controllers performed better in different aspects and situations. Figure 9.4 illustrates the models of multi-story buildings tested on a shake table, while Fig. 9.5 shows the passive tuned mass damper of the Taipei 101. Both of these methods are designed as earthquake protection measures—their passive nature guarantees that no energy can be introduced to the building via improperly designed active control systems.

Active vibration damping systems with traditional industrial control methods are suggested by many publications, for example [13, 31, 32, 61, 68, 146]. Marzbanrad et al. essentially combines a classical LQ feedback loop with a feedforward loop

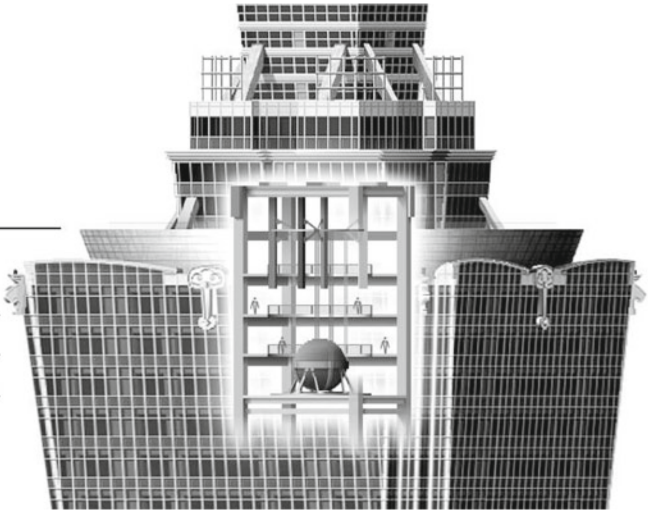


Fig. 9.5 Illustration of the scale of the tuned mass damper in Taipei101 [118]. To achieve better damping performance with smaller devices, passive tuned mass dampers may be replaced by active vibration control systems. Controllers must guarantee system stability and constraint feasibility at all times

acting as a sort of preview for the excitation to come [73]. In addition, residential and commercial buildings, vibration damping technologies have been suggested for bridges as well [89, 100]. State-feedback $\mathscr{H}_\infty$ optimal control is described in [45, 100] to implement earthquake protection in buildings. Asymptotic stability of the controllers is investigated and guaranteed in the work of Karimi et al. Piezoelectric actuators are uncommon in seismic vibration control because of the questionable range, however they are featured with a positive position (acceleration) feedback strategy in [103]. A SMA-based earthquake protection system is suggested in [130] by Torra et al. Fuzzy control with stability guarantees is considered in [50] suggesting that researchers in earthquake engineering do acknowledge the importance of a priori stability guarantees as well.

Other civil engineering applications include the vibration control of disturbances created by impulsive loads such as blasts and explosions. El Wahed et al. proposed both an ER and an MR fluid-based blast resistant structure for applications in structures such as offshore drilling platforms in [137]. According to the abstract, the vibration control of an elevator is solved by multi-parametric progamming in the Chinese language paper by Ping and Ju [94].

9.7 Manufacturing, Machinery and Tools

Vibration in manufacturing and machinery contributes directly to financial losses and products with decreased quality. For example, the lateral vibration of the spindle in high-speed lathe machines causes manufacturing errors and significantly contributes to machine failure.

This section reviews active vibration control applications in the field of rotor systems, active mounts and power tools. Of these works by Bai and Ou and Shi et al. utilizes traditional predictive control formulation in a closed form [6, 108], while [19] utilizes a constrained explicit MPC control scheme. Another interesting application of MPC in machinery is the low frequency load-sway attenuation in cranes presented by Neupert et al. in [87]. Neither active vibration isolated platforms nor machines have a known use of the model predictive control strategy yet.

9.7.1 Rotor Systems

Vibrations in rotating systems such as shafts may appear due to imbalance, misalignment and outside disturbances. Linear voice coil motors are utilized in [6] to attenuate the transverse vibrations of a shaft. The work of Bai and Ou utilizes older FIR-based predictive control and GPC concepts without constraint handling. Because of the lack of constraints, the predictive control law is derived directly in a close form. The question of stability is treated by the experimental variation of tuning parameters; however, an a priori stability guarantee is not given. The authors pointed out that the GPC algorithm outperformed the FIR-based predictive controller.

Dynamic matrix control—a traditional step response-based algorithm—is used in [108] in cascade with a PI controller for the control of a two-mass rotational drive system. Although this work is not specifically for vibration control, its results apply to this field as well. The unconstrained MPC control law in a closed form does not utilize the full potential of the contemporary results of predictive control theory.

A considerably more up-to-date approach is utilized for the same physical problem by Cychowski and Szabat in [19]. The work implements an explicit, MP-based MPC controller in real-time on a two-mass drive system with good results. The implemented MPMPC control law is constrained, however stability guarantees are not given and the subject is not treated in this work. The sampling time selected for this work is 500 μs and with the number of regions not exceeding 90 the worst-case computational time is less than the half of the sampling period. We have to note that a potentially larger region of attraction and a resulting longer prediction horizon would be needed with stability guarantees—resulting in a MPMPC controller with more regions. Given the nature and dynamics of the two-mass drive system, an explicit MP-based MPC approach is a good choice.

In addition to practically eliminating friction, active magnetic bearings (AMB) also control the vibration levels of rotating machinery. Such a system is discussed for example in [42], where the prevailing control strategy to use is $\mathscr{H}_\infty$. AMB systems can be regarded as hard to control because the underlying dynamics is unstable, multivariable, coupled and nonlinear with uncertainties [42]. Moreover, due to the general physical configuration of such rotor systems, often resonant frequencies over 500 Hz are to be expected, which make MPC implementation difficult.

The asymmetry between actuation capabilities and disturbances is not significant, therefore much shorter prediction horizons are expected than in the case of flexible, lightly damped systems. Magnetic systems are not the only way to damp rotor vibrations: a magnetorheological fluid-based semi-active system is featured in [156] while an ER fluid-based rotor vibration damper is presented in [11].

9.7.2 Active Mounts and Production Systems

The increased interest of the scientific and manufacturing community on micro-electromechanical systems (MEMS) demands manufacturing platforms, which are virtually free of vibrations. Such outside disturbances include micro-vibrations from the ground, instrument movement in the laboratory, people etc.

An effective way to overcome these vibrations is again active or semi-active vibration control. Various traditional control strategies are common for platforms, however to the knowledge of the authors no MPC-based vibration insulation platform has been presented to this date.

Magnetorheological damper-based semi-active vibration control mount platforms are presented in [16, 43]. Even though such a physical system is inherently stable because of the inability of the MR damper to inject energy into the structure, the presence of constraints may warrant a control system with stability guarantees. In other works, magnetostrictive actuators are used for the vibration control of a micromachining platform [153]. The use of piezoceramics is also very common for vibration damping in micromachining platforms.

Automatic manufacturing and production systems have an advantage over other applications mentioned here because the source of disturbance causing oscillations and vibrations is constant, periodic and well defined. Moreover, the source of disturbance is usually limited to the drive system and intermediate mechanisms [40, 97], therefore an active vibration control system is not necessary nor is it recommended. As the feedback sensing of these systems is often very expensive or not practical, traditional approaches may be recommended instead of MPC. Control strategies without feedback for systems such as filling of open containers with liquids in a production cycle may be very effective in reducing spillage [96]—as it has been demonstrated by experiments with liquid filled containers, displaced by a strategy with acceleration input shaping [40, 95].

9.7.3 Anti-Sway Control for Cranes

To make the operation of boom cranes more efficient, the loading and unloading time of cargo has to be shortened. This can be achieved by performing faster maneuvers by the crane operator, which in turn may result in significant unwanted oscillation of the load. This load oscillation is referred to as sway and it is easy to find the analogy with vibrations. Traditionally the load sway is compensated by the operator, however due to the need for the further decrease of loading times, automatic compensating techniques have found their way into this industry as well. Such commercial systems are already implemented: offering reduced sway, increased velocity, turnover and safety [64].

Hubinský proposed a strategy to control load sway and residual oscillations in cranes by feeding the drive system with acceleration signals subject to an input shaping strategy [40]. The slow oscillation times of loads in this application suggest that the sensing of the vibration levels cannot be realized by piezoceramic transducers [40], instead in the interest of simple practical realization a direct approach without feedback has been suggested. Because the load sway in cranes is caused mainly by the movement of the drive system itself, input shaping of drive acceleration profile may reduce load oscillations dramatically [40]. We have to note, that this strategy does not take into account outside disturbances such as wind, imbalance of the load due to non-uniform mass distribution and dynamic changes in inertia.

To tackle the load swaying issue, an MPC-based concept controller has been proposed by Neupert et al. in [87]. After creating a simplified linearized model of the load and crane dynamics, the tracking controller is formulated as a finite horizon, constrained, linear[3] MPC control problem. Natural constraints also arise by the configuration of the physical space, in which the load can be manipulated and transferred safely. These boundaries are then transferred and defined as actuator constraints in the predictive control problem. Additionally, the controller features velocity and acceleration (in other words rate constraints), which have been designed to prevent resonance created by over-aggressive actuator action.

The physical problem on which this concept controller has been evaluated is a large harbor crane, the LIEBHERR Harbour Mobile Crane LHM 400, illustrated[4] in Fig. 9.6. Since the crane features a rope length of up to 90 m, the swaying periods can extend to 19 s or roughly 0.05 Hz. In terms of vibration attenuation, this is a system with very slow dynamics. Referring to practical experience, a control horizon of $n_c = 10$ steps has been utilized in [87], with a sampling of $T_s = 1$ s.

The problem of controller stability in the work by Neupert et al. has been treated by a zero state terminal constraint. This fixed equality constraint eventually has been discarded and replaced by an extension of the quadratic cost function with a terminal penalty term. Neupert et al. has abandoned the idea of using terminal constraints because under non-nominal conditions such as plant-model mismatch and with short horizons these constraints would render the MPC problem infeasible.

Instead of the above-mentioned solution, the feasibility and stability of the MPC controller could be ensured by using the well-known dual-mode infinite horizon MPC formulation with a polytopic terminal set. Feasibility of the constraints and stability beyond the prediction horizon is ensured by the addition of additional constraints determined by the length of a constraint checking horizon. However, this formulation would also create a problem similar to the one already discussed: states would be

[3] Due to the nonlinearity of the load behavior, the authors utilize linearization of the actual dynamics.

[4] Courtesy of Liebherr.

(a) LHM 400 crane **(b)** LHM 400 in operation

Fig. 9.6 LIEBHERR Harbour Mobile Crane LHM 400 [65]. A drawing of the crane is shown in (**a**), while (**b**) illustrates the LHM 400 in operation

contained within the region of attraction, while the size of this region has to cover all the expected conditions, otherwise the optimization problem may become infeasible.

Let us look at the given harbor crane problem in detail and assess whether there is an analogy between lightly damped and under-actuated vibrating systems: The controller should cover the highest resonant frequency of the system, which has considerable effect on dynamics. For a vibrating mechanical system it is often enough to consider the first dominant resonant frequency to approximate the dynamics. However, in the case of a boom crane, we have parametric vibrations—with the cable length l_c being our governing parameter. Let us represent the swaying load with a mathematical pendulum. For small amplitudes the oscillation frequency approximated by

$$f = \frac{1}{2\pi}\sqrt{\frac{g}{l_c}} \tag{9.1}$$

where f is the approximate oscillation frequency, g the local gravitational constant and l_c the rope length. A maximal rope length of 90 m produces a very slow 0.05 Hz oscillation, but as the rope gets shorter, this oscillation frequency increases. For a 10 m rope the oscillation increases to 0.16 Hz, while a 1 m rope causes swaying motion with 0.5 Hz motion (Fig. 9.7).

A boom crane actuated by powerful hydraulic pistons and motors is nowhere near as underactuated as a mechanical structure damped by piezoelectric patches. In the case of a crane we may safely assume that for the slowest sway motion of 19 s it takes about the whole period to return the system near to its equilibrium, that is to get the system state back to the target set. To account for the shorter end of the rope length spectrum, one would require 10 Hz sampling, that is 0.1 seconds. To create

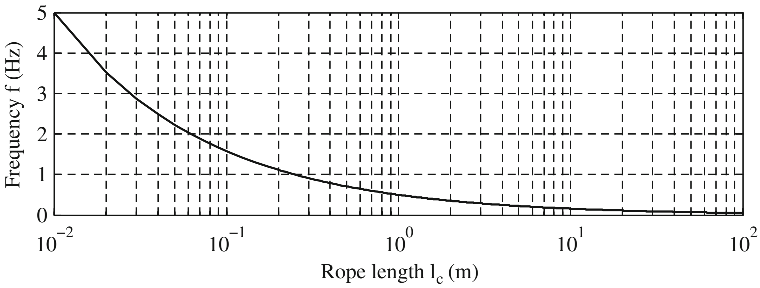


Fig. 9.7 Resonance frequency depending on actual rope length l_c on a crane

a controller capable of keeping up with the fastest resonance, while having a safely exaggerated volume of the region of attraction we would need a prediction horizon in the order of $n_c = 100$–200 steps. To compute such a controller online with a 0.1 s sampling may, or may not be an issue—that depends mainly on the model order.

From the above consideration, it is clear that implementing a model predictive controller with polytopic stability and feasibility guarantees may not be trivial for this system, which resembles many of the characteristic issues of under-damped flexible systems.

9.7.4 Machine Tools

Chatter suppression is solved by using an ER fluid based semi-active system for a boring machine in [138]. Albizuri et al. solves the chatter suppression of centerless grinding machines in [3]. Certain common household items such as washing machines can also benefit from semi-active or active vibration control [119]. The authors of this book have not been able to find an example of an MPC strategy-based vibration reduction application for industrial or household machines.

The power tool manufacturing company DeWALT markets its line of power tools—mainly rotary hammers and demolition hammers—with the (marketing) statement that they are enabled with “Active Vibration Control”. Although these tools do have a form of vibration control, it is certainly not active: currently a spring loaded tuned mass is utilized for damping in the aforementioned product line [21]. According to the company, this passive approach decreases handle vibrations in the work axis by 70% while the overall vibration levels are decreased by 30% thus increasing work comfort and component lifetime. Another power tool manufacturer Hilti also markets some of its products with “Active Vibration Reduction” since 1998. Again, while this technology can effectively improve working conditions and prevent hand-arm vibration related injuries, it is not active in the scientific sense. The approach in Hilti products rests on mechanism and tool shape optimization, passive vibration isolation and tuned mass dampers [36].

9.8 Vibration Control in Aircraft and Spacecraft

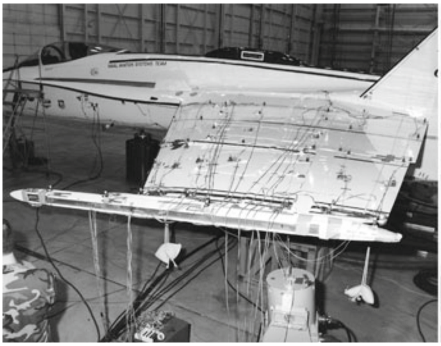
Increased government spending in the military and space sectors has always fueled active research of new technologies. This desire for military and scientific superiority ensures that new ideas are readily implemented and accepted in highly specific fields such as space flight and military aviation.

To the knowledge of the authors, there are currently no implementations of model predictive control for spacecraft or aircraft vibration control. This holds true for both (known) practical implementations and for academic literature. This section will briefly characterize some of the currently available works on the vibration control of spacecraft and aircraft and introduce some basic concepts and terms used in the application field.

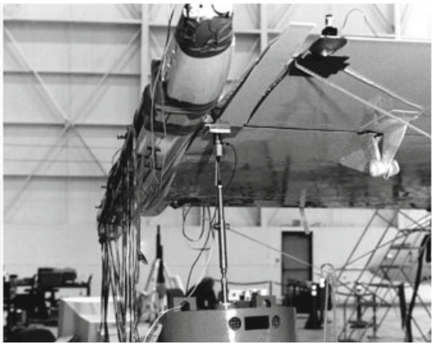
9.8.1 Aircraft Vibration

Active vibration control may enhance the flight properties of fixed and rotary wing aircraft, reduce weight and increase passenger comfort. Since structures in aviation are not completely rigid, some interactions will always occur between the inertial and elastic properties of aircraft structures and aerodynamic forces. This phenomenon in short is referred to as *aeroelasticity*. In the presence of outside aerodynamic forces, the aircraft structure will deform. This deformation is then a ground for increased force interactions, thus creating a self-feeding deformation and disturbance cycle. In other words, the aeroelastic phenomena may be understood as a type of unintentional positive feedback process. There are two types of aeroelasticity: static and dynamic, of which the latter much resembles the characteristics of vibrating structures.

The aerodynamic forces may excite the structure to vibrate in one or more of its resonant modes, creating a potentially dangerous and destructive situation. This effect is referred to as *flutter* in aviation and although it is not identical to the forced resonant phenomena presented in Sect. 2.3—its attenuation requires similar tools and methods. Another common dynamic effect is called *buffeting* and it refers to the excitation of the structure by random impulse-like forces due to the separated flow surfaces. The periodic vibration of aircraft structures is undesired and can be effectively damped using active technologies. Active aeroelastic control of fixed-winged aircraft through a transfer function based approach is considered for example in [14]. The control systems of aircraft responsible for setting control surfaces may also contribute to flutter; this is referred to as *aeroservoelasticity*. Unlike the control strategies utilized currently, MPC may enhance flutter avoidance by explicitly handling constraints arising from actuator limitations and the mechanical properties of the structure. Active aeroelastic surfaces in fixed wing aircraft are have been actively researched



(a) Modified F/A-18A with visible accelerometers



(b) Shaker test of the active aeroelastic wing

Fig. 9.8 The upper wing surfaces of the Active Aeroelastic Wing F/A-18 test aircraft are covered with accelerometers and other sensors during ground vibration tests at NASA Dryden Flight Research Center in (**a**) [132], while (**b**) shows a large shaker connected to the instrumented wing surface in a dynamic test [131]

in the not so distant past: Fig. 9.8[5] shows the modified F/A-18A research test aircraft with an active aeroelastic wing developed by NASA [57, 131].

As the dominant resonances occur near 20 Hz in aerospace applications, from the viewpoint of computing efficiency it is likely that model predictive control is a feasible implementation choice. Wing tip surfaces are flexible and embedded actuators such as piezoelectric patches cannot effectively match the energy introduced by the disturbances. This in practice means, that a controller with stability guarantees must have a large region of attraction—as it will be demonstrated in the next chapters using the simple cantilever beam demonstration system.

The vibration control of the tail section of military fighter aircraft are of special importance. Fighter aircraft spend a substantial amount of the flying hours in high angles of attack, in which the dynamic loads on the tail are especially high [25]. Vibrations of the twin-tail section of an F-15 military aircraft have been damped by a velocity based feedback control law in [25] using piezoelectric actuators. Another work employing the velocity feedback strategy for aircraft tail sections is featured in [24] also providing stability analysis of the suggested system. Parametric stability of a nonlinear dynamic model of a twin aircraft tail has been investigated with a closed-loop feedback controller later in [4]. In addition to the control of wing surfaces to prevent flutter and other aeroelastic effects, similarly to the automotive industry there is an interest in the application of MR dampers in landing gear [5].

The noise from civilian and military aircraft is also a problem, especially in densely populated areas. Jet engines produce two types of noise: a low-frequency component dominates at takeoff and climb, while a higher pitched sound is audible at landing maneuvers [104]. Passive counter-measures like high-bypass-ratio jet engines offer a significant noise reduction, which could be further improved with active strategies.

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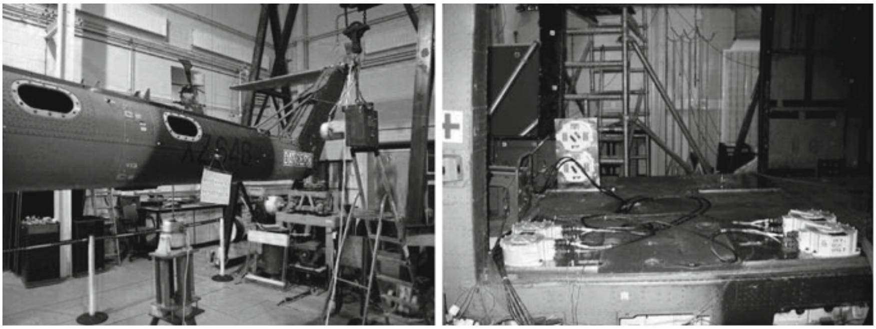
[5] Courtesy of NASA.



(a) Shaker test on a helicopter tail **(b)** Force actuators shown in the fuselage

Fig. 9.9 Electrodynamic shakers are connected to the tail section of a military helicopter in (**a**), while (**b**) shows the magnetic force actuators mounted in the fuselage [88]

In addition to the jet engine noise, passenger comfort may be increased by using active panels and linings inside the fuselage.

Fixed-winged aircraft is not the only area of application of active vibration control in the aviation industry. Rotary wing aircraft—or helicopters are subject to strong dynamic disturbances as well. Vibration damping in helicopters can be divided into three basic approaches [8]:

- Vibration control of the fuselage, actuators on the fuselage
- Vibration control of the fuselage, actuators on the rotor system or individual blades
- Vibration control of the rotor system or individual blades

An illustration of a dynamic test performed on a helicopter tail section is featured in Fig. 9.9.[6] Here the outside disturbance caused by the tail rotor is simulated by large shakers and the vibration levels inside the fuselage are attenuated using force actuators.

The flight speed record in helicopters has just recently been broken by the Sikorsky X2 helicopter prototype [117]. The enhanced horizontal flight and hovering capabilities and the flight comfort of the aircraft is partly due to the implemented active vibration control system [116, 117]. Other commercial aircraft, for example the Sikorsky 76D or the Sikorsky S-92 already features a type of active vibration control system, implemented through a nose or rotor hub mounted pair of force actuators [113, 114]. Military aircraft like the Sikorsky UH-60M (Blackhawk) technical sheets also list active vibration suppression systems, however implementation details of these technologies are proprietary [115]. The upcoming active rotor hub mounted vibration system may feature semi-active magnetorheological actuator based damping. Although there is not much information on the technology, recent press releases suggest the involvement of an outside contractor specialized in magnetorheological dampers [112].

[6] Courtesy of the Noise & Vibration Control Ltd.

Other major helicopter manufacturers and airspace or defense contractors have also successfully implemented experimental vibration reduction systems. Vibrations are reduced below 0.05 G at 4/rev and 8/rev speeds in a Kawasaki BK117 helicopter [47]. Fuselage vibrations are semi-actively damped in the HAL Dhruv Advanced Light Helicopter, where four isolation elements are mounted between the main gearbox and the fuselage [30, 70]. The same magnetorheological damper based technology is used in the Eurocopter EC225/EC725 [70].

Shape memory alloy materials have been used in experimental rotor blade systems to control stiffness, blade angle twist, natural frequency and damping properties in [59]. Vibration control of individual rotor blades is discussed in [8]. Coupled fuselage-rotor modes are damped in a rotary wing unmanned aerial vehicle (UAV) using positive position feedback in [2]. A very interesting idea is presented by Lu and Meng in [71], where the authors suggest the use of an ER fluid filled composite plate. Such novel materials can possibly shift frontiers on the active vibration insulation of air and spacecraft.

The flutter control of helicopter rotors has a related problem area in the field of power generation: TingRui and YongSheng have investigated the aerolastic behavior of wind turbine blades in [69].

9.8.2 *Spacecraft Vibration*

The vibration resistance of space structures ranging from rockets, orbiters, satellites, space telescopes is an important design factor. These engineering structures are subjected to rigorous vibration testing at their design stage to investigate their dynamic response. For example Fig. 9.10[7] shows the now retired space shuttle and its components undergoing vibration testing [79, 83, 84], while Fig. 9.11[8] shows a space station component and a probe in vibration testing as an illustration [82, 85]. Spacecraft undergo weeks of intensive thermal and vibration testing to imitate the temperature and dynamic forces encountered at launch and spaceflight [85]. Any measure increasing the vibration resistance of spacecraft can improve the safety of both manned and unmanned spaceflight and decrease the cost of cargo transportation into space. Active vibration control may have a role in the design of future economic and reusable spacecraft, which became an actual issue after the recent termination of the space shuttle program and the last flight of the orbiter Atlantis STS-135 into outer space.

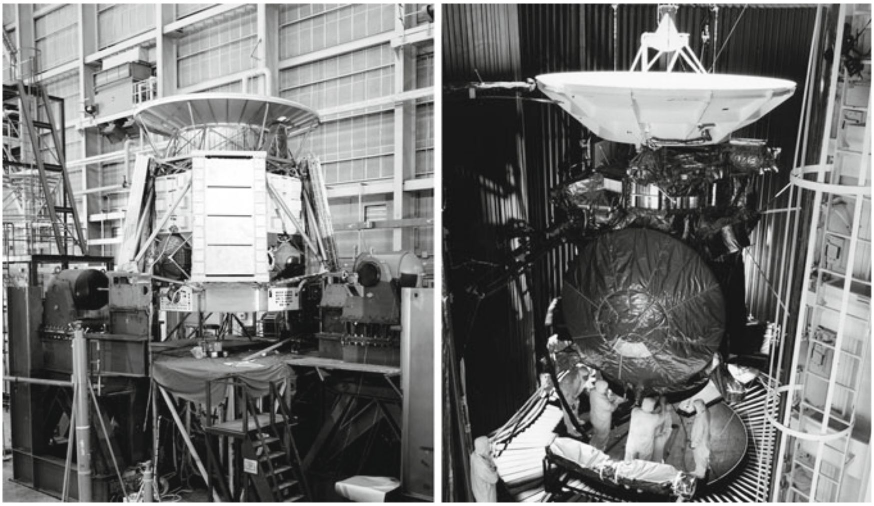
The worst-case loading scenario for a payload such as a satellite is its launch. Payloads, for example the previously mentioned satellites, have to be designed for this worsened condition, adding considerable cost to both the manufacturing process and the launch itself. This cost increase is mainly due to the passive vibration insulation and damping precautions, which add weight to the space vehicle and the payload.

[7] Courtesy of NASA.

[8] Courtesy of NASA.

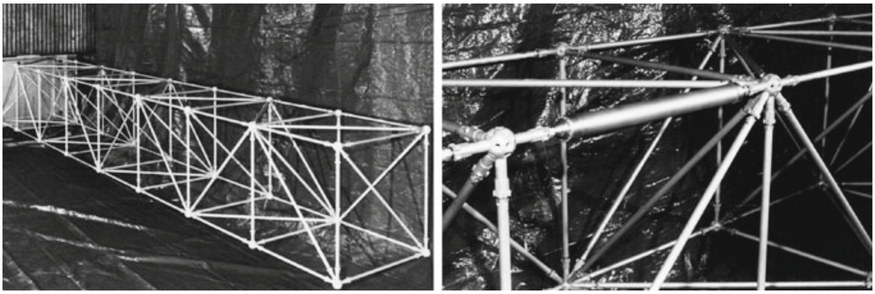
(a) Orbiter Enterprise in test stand installation **(b)** Removal of orbiter Enterprise from test stand **(c)** Mobile launcher platform and solid rocket boosters

Fig. 9.10 The photograph (**a**) shows the now retired orbiter (space shuttle) Enterprise in its liftoff configuration undergoing a dynamic vibration test, its removal from the stand in (**b**) and the ground vibration test of a mobile launcher platform with the solid rocket boosters in (**c**) [79, 83, 84]



(a) Apollo telescope mount **(b)** Cassini Saturn probe

Fig. 9.11 The Apollo telescope mount, one of four major components is undergoing horizontal vibration test in (**a**), while (**b**) shows the Cassini Saturn probe in a similar vibration and thermal testing scenario [82, 85]



(a) Space truss under vibration test **(b)** Passive damping element in space truss

Fig. 9.12 A space truss undergoing vibration tests on a trust-boom test hardware is presented in (**a**) [80] while (**b**) [81] shows a passive damping element within the space truss

The payload within the capsule is secured using the so-called payload adapter fitting (PAF). Traditionally PAF have been predominantly rigid structures absorbing little of the launch vibrations. Recently passive approaches have emerged and successfully flown to space, considering vibration damping when designing PAF. The other approach is to replace the PAF with an actively controlled structure.

A whole spacecraft-based active vibration isolation scheme is proposed in [28], where MPC is used to track pressure for a pneumatic actuator. In fact, this approach uses MPC not to directly control the vibration levels, but as an inner loop of a two-controller cascade—therefore cannot be considered as an example of MPC-based vibration suppression scheme. The MPC law is responsible to track desired pressure levels in the actuator, while the vibration control itself is taken care of by a simple rate-feedback controller. The MPC law used in [28] does not assume constraints; therefore, it has been expressed as a closed feedback law. No computational issues arise from such an implementation, which essentially ignores real actuator limits and the question of controller stability.

The vibration of a smart grid structure resembling the configuration and dynamic behavior of solar panel structures is actively controlled using simple position feedback in [55]. Similarly, classical position feedback control is utilized in [37] for the vibration control of flexible spacecraft. The vibration suppression for inter-satellite communication links is presented in [72].

An application field closely related to space flight are robotic manipulators discussed in Sect. 9.2. In addition to the manipulators discussed earlier without an explicit intention to use in microgravity environment, for example [139], deals with a fuzzy controlled manipulator with piezoelectric patches for space.

The vibration attenuation of space borne optical interferometers is a great interest of the scientific community [99] as well. Such systems are based on large flexible systems in the range of 10 m while the optical stabilization has to be carried out at a 10 nm level. Such a vibration attenuation system is presented, for example, in [86]. The vibration attenuation of any space borne truss structure is of great interest in aeronautics. Figure 9.12[9] shows a trust-boom structure undergoing vibration testing with a passive damping element [80, 81].

Large flexible antenna systems in space are also an exciting field for novel MPC applications. A vibration control system for such an application has been suggested by Agrawal and Bang in [1]. The wind-induced vibrations of a ground-based parabolic radio telescope are damped by ER fluid-based actuators in a simulation study by Su et al. in [120].

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[9] Courtesy of NASA.

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