Active Vibration Control of Multibody Systems

Application to Automotive Design

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Abstract

Active vibration control to reduce vibrations and structure born noise is considered using a powerful multi-disciplinary virtual design environment which enables control system design to be considered as an integral part of the overall vehicle design.

The main application studied is active automotive engine vibration isolation where, first, the potential of large frequency band multi-input multi-output H2 feedback control is considered. Facilitated by the virtual environment, it is found necessary to take non-linear characteristics into account to achieve closed-loop stability.

A physical explanation to why receiver structure flexibility insignificantly affect the open and closed-loop characteristics in case of total force feedback in contrast to acceleration feedback is then given. In this context, the inherent differences between model order reduction by modal and by balanced truncation are being stressed.

Next, applying state-of-the-art algorithms for recursive parameter estimation, time-domain adaptive filtering is shown to lack sufficient tracking performance to deal with multiple spectral components of transient engine excitations corresponding to rapid car accelerations.

Finally, plant non-linearity as well as transient excitation are successfully handled using narrow band control based on feedback of disturbance states estimates. To deal with the non-linear characteristics, an approach to generate linear parameter varying descriptions of non-linear systems is proposed. Parameter dependent quadratic stability is assessed using a derived affine closed-loop system representation.

This thesis also considers actuator saturation induced limit cycles for observer-based state feedback control systems encountered when dealing with the active isolation application. It is stressed that the fundamental observer-based anti-windup technique could imply severely deteriorated closed-loop characteristics and even sustained oscillations. That is in the case when the observer is fed by the saturated control signal in contrast to the computed one. Based on piecewise affine system descriptions, analytical tools to conclude about limit cycles and exponential closed-loop stability are provided for the two observer implementations.

Keywords: Active Vibration Control, Vibration Isolation, Feedback Control, Adaptive Filtering, Saturation, Limit Cycles, Multi Body Systems, Modelling, Simulation, Non-linearity, Gain Scheduling, Structure Flexibility

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To Martina
Appended Papers

This thesis contains an introductory part and the following six appended papers formatted for uniformity.


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Fierce competition is a significant characteristic of today’s market for passenger cars. In order to be competitive and to meet legal demands, automotive industry is forced to develop vehicles that possess improved comfort, safety, and quality, reduced weight and fuel consumption, as well as lowered emission levels. Simultaneously, the product cost has to be reduced while the time for product development, including steps from initial product concept development to a commercially available product, is shortened.

On the other hand, the relative maturity of many traditional technologies within different technical areas, implies little or no potential for improvements. Consequently, to deal with the technical challenges associated with some of the above mentioned requirements, non-conventional techniques have to be introduced where the conventional ones have already reached their limits. This is especially true in the field of noise, vibration, and harshness (NVH), where the targets, considering cross-attributes balancing, are way beyond the scope of traditional passive insulators, absorbers, and dampers. Thus, active noise and vibration control (ANVC) techniques are then necessary. This technology enables improved balancing of various contradicting properties that are closely associated to one or several interactive subsystems. Moreover, it could also assist in overcoming limitations associated with the traditional passive solutions.

However, the potential benefits of incorporating ANVC technology in the product development are determined by the way it is introduced. As for any new technology, the ratio between product customer value and product cost has to increase for an implementation to be motivated. Furthermore, a large number of vehicle subsystems and complete vehicle attributes influence the NVH properties and the actual ANVC systems development requires a broad technical knowledge. All together, the above issues make a suitable utilisation...
of ANVC a great challenge, not least since the overall design prerequisites change due to the possibility of integrating active solutions into the complete automotive design.

In this thesis, components of a design strategy are identified that takes the above mentioned issues into account. Some of its potential is demonstrated dealing with several technical problems related to active vibration control (AVC), an ANVC technique to deal with unwanted vibrations as well as vibration-induced structure borne noise.
As defined in [16], the main objective of AVC systems is to reduce the vibrations of a mechanical system by modification of its structural response. These systems are composed by one or several sensors (to detect the vibration), one or several actuators (to affect the response of the mechanical system), and an electronic controller (to compute a signal which is to be fed to the actuators to achieve desired modification of the structural response). Thus, AVC is multidisciplinary [40] involving structural dynamics, control, signal processing, acoustics, material sciences, and actuator and sensor technology. In addition to vibration control, AVC are also used to reduce structure borne noise which is often induced by the vibrations (see e.g. [9, 12, 23, 27, 28, 34]). Yet, there is a clear distinction between these systems and systems solely devoted to active noise control (ANC) where the latter uses, for instance, loudspeakers to directly affect the sound field [11, 14, 18, 28, 41, 45, 46].

Traditionally, vibrations of mechanical structures are treated using passive damping and/or passive isolation. These techniques are effectively used in many applications but are inevitably associated with certain limitations. Passive damping is effective at high frequencies but tend to be large, heavy, and expensive for low frequencies. Vibration isolation is normally subject to conflicting requirements where the isolation elements need to be soft enough to reduce the transmission of forces, but stiff enough to prevent large relative displacements. In e.g. automotive engine suspension design, the latter is important considering the limited space of the engine compartment and the alignment requirement for possible connection of the engine to the intermediate and drive shafts. AVC is used to overcome limitations like these and has been applied to a wide variety of applications. In addition to passenger car applications it is, for instance, also applied to marine applications [9, 26], railway
vehicles [15, 33], vehicle seats [48], aircraft frames [7], helicopters [4], bridge towers [44], bandsaw blades [10], and telescope attitude control [42].

Similar to the different passive techniques to deal with mechanical vibrations, active vibration isolation and active vibration suppression are two terms categorising two distinct AVC strategies. As defined in [3], active isolation refers to the reduction of the force transmitted between structures at discrete connections whereas active vibration suppression refers to the reduction of a structure’s global vibratory response using control actuators at locations that do not coincide with the discrete power insertion points.

A common active vibration isolation application is active machinery vibration isolation which is achieved using a force actuator generating a secondary force to counteract for the primary excitation, i.e. the internal and/or external excitation of the mechanical structure generating the unwanted vibrations. Two main strategies for application of the secondary force exist [16]: (i) in parallel to a passive stage (i.e. combinations of passive damping and stiffness elements) both located between the machine and the receiving structure (see e.g. [13, 20, 43]) and (ii), directly on the receiving structure opposite to the point of attachment of the machine mount (see e.g. [1, 2]). The choice of method influences the magnitude of the secondary force required to cancel the vibrations of the receiver. To deal with vibrations for frequencies near and above the mounted natural frequencies of the machine, the parallel configuration requires lower secondary force magnitudes [16, 21].

One automotive AVC application is reduction of vibrations and structure borne noise induced by the engine internal excitation, which is due to gas pressure fluctuations and unbalanced rotating masses. As mentioned above, the engine suspension system of a vehicle is a typical example to which active isolation could be applied to deal with the limitations [17, 30, 31, 32, 35, 49, 50] of a passive system design, yielding an active engine vibration isolation system. A lot of attention has been paid to the solution of this problem by the use of active engine mounts [17, 19, 23, 24, 27, 28, 34, 36, 37, 39], i.e. by adopting the parallel actuator configuration. Still, the alternative isolation strategy using active absorbers attached to the receiver has also been investigated [5, 8, 22, 29].

Although many successful applications of AVC have been reported, there still seems to be issues which require further investigation to exploit more of the potential benefits of AVC technology. The following are some of such issues that concern a beneficial incorporation of AVC technology into the early stages of the automotive product development.

- How should the accessibility of various AVC solutions be made a natural part of the conceptual prerequisites of the complete vehicle?
- How could different combinations of passive and active system concepts be evaluated? This includes, for instance, the balancing of contradicting properties that are closely associated to one or several interactive subsystems, as well as choosing between different conceptual AVC solutions
based on different control strategies and different numbers, types, and locations of actuators and sensors.

- How should passive system design be carried out, to facilitate conceptual and detailed AVC system design, and to yield effective active systems?
- How should, for the purpose of controller design, sufficiently accurate models of the system to be controlled best be generated to ensure satisfactory AVC system performance?

In addition to the above mentioned overall questions which are closely related to the design process, there are also more technical issues such as

- What are the impacts on controller design of various dynamic attributes such as structure flexibility, non-linearity, actuator limitations, time varying excitation characteristics, time varying plant characteristics due to *e.g.* ageing and heating, and uncertain passive element properties?
- What are the most suitable control strategy (*e.g.* time and frequency domain adaptive filtering, feedback, etc.) with respect to each specific AVC problem and the corresponding excitation characteristics?
- How to deal with model reduction considering control object models having large number of degrees of freedom to fulfill the requirements for real-time implementation of model-based controllers?

To deal with many of the above mentioned issues, it seems to be necessary to, in early product development phases, consider AVC system design as an integrated part of the complete vehicle design.
Active Vibration Control in Automotive Design

In the AVC literature, it appears customary to consider AVC systems as isolated subsystems to be added to existing definitive passive designs. Naturally, it is sometimes motivated to utilise AVC to overcome problems associated with a passive design discovered in a late product development phase. Still, this way of introducing AVC solutions is likely to imply increased weight and cost of the final design which is unfavourable considering the hyper-competitive operating environment of the automotive companies.

To motivate the utilisation of AVC in automotive design and to maximise its advantages, the issues listed in Chapter 2 (and possibly others) have to be addressed. Consequently, AVC technology has to be considered in the concept development phase and treated as an integral part of the overall vehicle design prerequisites. These new premises created by introducing AVC systems are used to achieve optimal product performance by integrating active and passive design in early design stages. This also enables passive system design that maximises the effectiveness of the active system. Here, an effective active system e.g. refers to a system with high performance to a low power consumption.

In the AVC literature, very limited attention has been paid to the issue of integrated passive and active system design, and to suitable design strategies for maximisation of the potential benefits of AVC. Yet, there are initiatives stressing the importance of considering the systems for vibration damping as an integral part of the complete vehicle design [5, 25, 30, 32]. In [5], the authors suggest redesign of a passive engine suspension design to achieve dominant transmission paths where active isolation is to be applied. This is one example of integrated active and passive system design where the passive system is adapted to increase the efficiency of the AVC system. Studies on suitable design strategies have also been carried out. In [6, 8], the design, simulation,
Active Vibration Control in Automotive Design

and implementation of automotive AVC systems are considered. Yet, only the
design steps following concept development are mentioned and, once again, a
more or less definite passive system design is assumed.

Dealing with the above mentioned issues together with car industry’s de-
mand for shortened lead-times, the automotive design process has to be sup-
ported by an efficient multi-domain virtual design environment based on re-
liable modelling and simulation of dynamics and control systems. Such an
environment, enabling concept evaluation, analysis, and verification, has also
to facilitate the treatment of the following issues

- Accurate modelling of control objects which are likely to have a large
  number of degrees of freedom
- Balancing of different targets and interacting attributes
- General input/output relationships to deal with e.g. various combina-
tions of actuator and sensor locations and different number of sensors
  and actuators
- Non-linear characteristics and flexible bodies
- General load cases including random and deterministic excitation
- Efficient control synthesis
- Generation of analytical representations of equations of motion for con-
troller design purposes
- Evaluation of different active concepts in the early product development
  phases when, possibly, no prototypes exist
- Evaluation and analysis of passive/active system interaction with respect
to each conceptual solution including both passive and active ingredients
- Closed-loop verification in time domain to e.g. verify the active system
  stability and performance
- Model reduction to obtain models suitable for model based control
- Optimisation to maximise the performance of a specific active/passive
  concept

An environment that complies with the above mentioned requirements
needs to combine several tools for controller synthesis, simulation of controller
functionality, control algorithm rapid prototyping, as well as dynamic systems
modelling using e.g. softwares for finite element and multi body system (MBS)
modelling and simulation. Such a combination, which has been utilised in most
of the appended papers, is schematically illustrated in Figure 3.1.

An important quality of the required virtual environment is its simulation
capabilities. To accurately design and predict the performance and stability of
an AVC system, the structural response due to the controller output signal and
other disturbance sources has to be evaluated using sufficiently detailed model representations of the mechanical structure, actuators, and sensors. This evaluation should also cover the information that has been neglected in the controller design phase, such as e.g. unmodelled non-linear and high frequency characteristics. One way to achieve this is to use co-simulation\cite{47}, where two software tools are run concurrently, one simulating the control system functionality, and the other predicting the response of the mechanical structure including actuators and sensors. In Figure 3.1, the dashed lines illustrate the co-simulation signal flow between a tool for accurate MBS modelling and simulation, and one for simulation of the controller functionality.

Another important feature of a virtual environment like the one depicted in Figure 3.1, is the possibility to extract analytical model representations of

**Figure 3.1** A schematic picture of a multi-domain virtual design environment including tools for modelling, control synthesis, co-simulation (illustrated by the dashed lines), and rapid prototyping (FEM stands for Finite Element Modelling).
general input/output relationships. By this functionality, models for controller synthesis could effectively be obtained and thus, model based controller design easily adopted. It is also possible to use this feature to, for instance, study the impacts on controllability and observability of specific vibration modes, with respect to different sensor and actuator configurations. Not only linearised model representations could be directly extracted, but also analytical models of structures including non-linear characteristics could sometimes be obtained [38].

In contrast to the design strategy outlined above, the most widely used AVC system design approach is based on experiments where representations of the control object dynamic characteristics are obtained using system identification. This approach has been used to produce satisfactory designs but are also associated with a number of limitations. The main drawback is the requirement of a physical prototype. Thus, the design of the passive mechanical structure has to be more or less finalised, leaving the question about the best combination of passive and active solutions unanswered. Furthermore, a number of questions seems to be difficult to address using this approach, where the following list raises some

• What is the expected achievable performance?
• What are the mechanism limiting the performance?
• What are the impact of a specific modification to the passive concept?
• Is there a more effective sensor and actuator configuration?
• What are the reasons for instability?

Using modelling and simulation, it is possible to gain an increased understanding of issues like these by e.g. studying non-measurable quantities. Thus, a design approach based on modelling and simulation, should be adopted as a preliminary and complementary step to the experiment-based one, where the latter is to be used primarily for final verifications.
SUMMARY OF APPENDED PAPERS

In this chapter, the appended papers are briefly summarised in chronological order to point out their main conclusions and reflect the evolution of the thesis work.

4.1 Paper I

The potential of broad frequency band feedback active automotive engine vibration isolation is considered. A multi-input multi-output controller design has been carried out making use of a virtual development environment (schematically shown in Figure 3.1) for design, analysis, and co-simulation based closed-loop verification. Utilising relevant control object dynamic modelling, this design strategy provides a powerful opportunity to deal with various plant dynamics such as non-linear characteristics. The main objective is to closely approach the true physical behaviour for control design and verification to achieve optimum product performance.

$H_2$ loop shaping technique proves potential when achieving the desired closed-loop characteristics. However, to achieve closed-loop stability two kinds of non-linear characteristics have to be taken into account. Those are non-linear material properties of the engine mounts and large angular engine displacements. It is demonstrated how the adopted design strategy facilitates the investigation of the latter non-linearity’s impact on closed-loop characteristics using Gain Scheduling. The proposed solution deals with system non-linearities and all possible engine excitations except those corresponding to very rapid changes and extremely high values (evoking non-linear material characteristics) of the nominal engine torques, for which the controller has to be turned off to ensure closed-loop stability.
4.2 Paper II

This paper considers $\mathcal{H}_2$ controllers implemented using an explicit observer for systems subjected to input magnitude saturation. It is pointed out that the approach of only focusing on controller windup, by using the fundamental observer anti-windup technique where the observer is fed by the saturated control signal, could imply severely deteriorated closed-loop characteristics and even sustained oscillations. This is illustrated by providing a simple single-degree-of-freedom dynamic system to which active vibration isolation has been applied.

Describing function analysis is adopted for approximate analysis. In the presented $\mathcal{H}_2$ control application, the existence of limit cycles is found to depend on the combination of control object characteristics and the choice of $\mathcal{H}_2$ weighting functions.

4.3 Paper III

The existence of saturation-induced limit cycles is further investigated for observer-based state feedback control systems. Two different observer based controller implementations are considered, one using the computed control signal for state estimation and the other using the control signal actually applied to the plant. Based on piecewise affine system descriptions, analytical tools to conclude about limit cycles and exponential closed-loop stability are provided for both implementations. The condition for limit cycles is found to involve the yet unsolved problem of spectral radius characterization of the product of two matrix exponentials. Furthermore, it is shown how to apply the method of separable nonlinear least squares to effectively resolve the provided analytical conditions for investigation of limit cycle existence.

Applying the derived conditions to a numerical example, it is demonstrated that while limit cycles exist in the case of an implementation using for state estimation the control signal applied to the plant, global stability could be proven for the alternative implementation utilising the computed control signal.

4.4 Paper IV

Active vibration isolation from an arbitrarily, structurally complex receiver is considered with respect to the impacts of structure flexibility on the open- and closed-loop system characteristics. Specifically, the generally weak influence of flexibility on the open-loop transfer function in case of total force feedback, in contrast to acceleration feedback, is investigated.

The open-loop system characteristics are analysed based on open-loop transfer function expressions obtained using modal expansion, and on modal model order reduction techniques. It is shown that when the contribution to the total transmitted force from either a rigid body, global flexible, or local flexible
eigenmode is small compared to the actuator force, it does not significantly contribute to the open loop transfer function. The factors determining the contribution from an individual mode are given where the mode direction relative to the actuator force direction is emphasised as a key factor. It is also pointed out that minor modal transfer function contribution has the physical interpretation of negligible passive stage force in the direction of the actuator compared to the actuator force. In this context, the relation between model order reduction based on modal and on balanced truncation is investigated. It is shown that for lightly damped systems with certain characteristics, the results when using balanced reduction techniques could potentially be very poor. In addition, the upper bound on the model perturbation due to state truncation is potentially very conservative in this case.

To closely demonstrate and illustrate the impacts of flexibility on the open-loop characteristics and on the closed-loop system performance and stability, the engine suspension system of Paper I is again envisaged. Here, automotive engine vibration isolation is considered taking flexibility of the subframe receiver structure into account. The consequences on performance and stability of neglecting flexibility in the controller design phase are investigated representing the introduced error as a relative output multiplicative model perturbation. For this application, the degradation of robust performance and stability is shown to be insignificant by the use of total force feedback.

4.5 Paper V

The AVC application of Paper IV is revisited. In this paper, the time domain adaptive filtering strategy widely used for active noise and vibration control has been adopted to deal with engine excitations corresponding to idle engine operating conditions and to rapid car accelerations including gear shifts.

The adaptive filtering problem is formulated using a linear regression model representation. This allows for an application of a general family of state-of-the-art recursive parameter estimation algorithms. The performances of two specific members of this family have been compared. Those are the well-known normalised least mean square (NLMS) algorithm and a recently suggested Kalman filter based algorithm originally proposed as a method to avoid covariance windup referred to as Stenlund-Gustafsson (SG). A virtual non-linear 43 degrees-of-freedom engine and flexible subframe suspension model and measured engine excitation are used in evaluation of algorithm performance.

For this application, it is demonstrated how SG and the Riccati equation associated with it imply superior performance compared to NLMS in terms of trade-off between convergence and steady-state parameter estimation variance. It is also shown how SG could be adapted to suit piecewise stationary conditions. However, none of the algorithms possessed sufficient tracking properties to deal with transient excitations corresponding to rapid car accelerations.
4.6 Paper VI

In this paper, the engine vibration isolation application of papers IV and V is further studied to address problems not yet fully solved. Consequently, both transient and stationary engine-induced excitations, receiver structure flexibility, as well as plant non-linearity are closely dealt with.

A control strategy targeting the dominating spectral components of the excitation and achieves narrow band vibration isolation using feedback of disturbance states estimates, is adopted. To effectively deal with the active system complexity, time-varying gain-scheduled observer design is carried out to achieve robustness to plant non-linearity in contrast to the alternative design approach of incorporating plant non-linearity into the controller. Both observer design and investigation of closed-loop characteristics are based on a linear parameter varying (LPV) description of the considered non-linear engine and subframe suspension system. Parameter dependent quadratic stability analysis is made tractable using an affine closed-loop system representation. To generate the LPV-representation of the non-linear system, an approach of dividing it into its linear and non-linear components where the latter is represented using a parameter dependent non-linear function, is proposed.

Excellent performance is demonstrated using co-simulations incorporating a detailed non-linear plant model and measured engine excitations. This is also achieved for engine operating conditions corresponding to rapid car accelerations, whereas the system exhibits non-linear characteristics and the fundamental frequency of the harmonic disturbance undergoes rapid time variations. Parameter dependent closed-loop quadratic stability is being shown assuming plant linearity. Thus, the adopted approach for closed-loop stability analysis is shown to be useful when dealing with the considered controller structure for linear time invariant plants. Yet, in the non-linear plant case, stability is guaranteed but only for limited intervals of the parameters and their time derivatives.
A trend towards fully integrated active and passive automotive design is natural since, on one hand, the efficiency of the active systems is determined by the passive system design and, on the other, the prerequisites of the passive system design are directly influenced by the active system operation. Yet, a development of the design process towards an increasing degree of such integration is conceivable.

A design example that represents limited degree of active/passive integration is minimising the non-linear characteristics of input/output relationships of active systems and, thus, facilitating controller synthesis. Carrying out passive design to minimise the number of actuators while maximising their efficiency is another one. A suitable choice of feedback sensor type could to a large extent reduce the required complexity of the control object model used in the controller synthesis [39], which could be considered as integrated active/passive systems design.

Using AVC to improve cross-attribute balancing constitutes a higher degree of active and passive system integration. This could, e.g., be applied to deal with the inherent compromise between NVH-properties and handling characteristics when determining stiffnesses of chassis bushings. Here, a special case is active engine mounts enabling higher dynamic stiffness in a frequency range of importance for handling and, at the same time, maintained or improved vehicle NVH-properties. Modified engine combustion-process control to increase engine efficiency by adopting AVC technology to deal with the, from NVH perspectives, generated less favourable engine excitation is another example. In this case, the increased degree of design freedom achieved by introducing AVC technology when optimising the combustion process could be used to reduce fuel consumption and thus, to improve product environmental impacts.
In addition to enhancing the conditions for cross-attribute balancing in automotive design, AVC could also be used to enable new technical solutions by creating extended margins or, equivalently, increased design flexibility. Such an example is given in [27] where an active engine mount system enabling varying number of engine cylinders in operation, is described. Using less number of cylinders during low load engine operations, the fuel consumption could be reduced. However, increased workload per cylinder implies higher combustion pressure and consequently higher engine vibrations amplitudes requiring isolation performance beyond conventional engine mounts. It is also conceivable that AVC could be used to enable new engine combustion technologies which are likely to require superior vibration isolation. Another example of utilising the extended margins provided by introducing AVC technology is the reduction of engine idling speed which positively affects the environmental impact. This normally causes excessive engine shake that requires, once again, excellent vibration isolation characteristics.

Finally, integrating AVC into the early design phases of the overall vehicle design is a great challenge for automotive product development organisations. This requires, for instance, an even better interaction between groups responsible for many different technical areas such as NVH, handling, strength and durability, powertrain design, powertrain installations, electrical architecture design, and active vehicle control system development. In addition, contacts with AVC-subcontractors of, e.g. actuators, have to be established in the very beginning of the product development process since the active element design and its achievable performance determine the prerequisites for the active and passive system integration.
Aktiv vibrationsreglering av flerkroppssystem

Tillämpat på personbilsutveckling

Personbilsmarknaden kännetecknas idag bl.a. av en extremt tuff global konkurrens som råder mellan producenterna. För att hålla sig konkurrenksksraftiga måste företagen inom personbilsindustrin ständigt förbättra utvecklingen av bilar med avseende på t.ex. ökad komfort, högre säkerhet, mindre bränsleförbrukning och lägre vikt. Samtidigt måste kostnad för utveckling, produktion, samt produkt sänkas och levtiderna kortas. För att hantera de tekniska utmaningarna förknippade med denna utveckling är det ibland nödvändigt att utnyttja ny teknologi för att skapa ökad utvecklingspotential. Detta gäller speciellt inom ljud- och vibrationsområdet där dagens användning av isolatorer, dämpare och absorberer, inte räcker till för att klara de ökande kraven.

Under arbetet med denna avhandling har beståndsdelar av en produktutvecklingsstrategi identifierats som möjliggör att aktiv vibrationsreglering, ett specifikt område inom aktiv ljud- och vibrationsreglering, betraktas som en integrerad del av ett nybilutvecklingsprojekts totala konstruktionsförutsättningar. För detta utnyttjas en effektiv multidisciplinär datormiljö för virtuell utveckling vars potential delvis har demonstrerats i behandlingen av flera specifika problem inom aktiv vibrationsreglering.

Aktiv isolering av motorvibrationer har tjänat som huvudsaklig tillämpning i hanteringen av de specifika forskningsfrågorna där potentialen i att använda bredbandig $H_2$-återkopplingsreglering med tre insignaler och tre utsignaler, först undersöktes. Genom att använda den identifierade utvecklingsmiljön konstaterades att denna strategi kan appliceras för att hantera körfall motsvarande kombinationer av låga motormoment och långsamt förändrade motormomentnivåer. Dock leder reglerstrategin till små stabilitetsmarginer vilket bl.a. kräver att regulatorn utnyttjar information om systemets olinjära egenskaper för att undvika instabilitet under vissa lastfall förknippade med höga motormoment.

Vidare har aktiv isolering av vibrationer från en mottagarstruktur med hänsyn tagen till denna strukturflexibilitet studerats. Här ges en fysikalisk förklaring till den låga påverkan av flexibilitet på det öppna och slutna systemets karaktäristik vid utnyttjande av kraftåterkoppling till skillnad från accelerationsåterkoppling. I samband med detta betonas den inneboende skillnaden mellan modellreducering baserad på balanserad respektive modal trunkering.

I syfte att undertrycka motorexcitationens dominerande frekvenskomponenter under både tomgångskörning och snabba bilaccelerationer applicerades sedan en inom aktiv vibrationsisolering vanlig metod baserad på adaptiv filtrering. I denna studie där en jämförelse av flera olika algoritmer för parameteridentifiering ingår, demonstreras bl.a. hur hyfsad prestanda kan uppnås genom att utnyttja de mest effektiva Kalmanfilterbaserade algoritmerna för rekursiv parameteridentifiering. Dock ger denna strategi inte tillräckligt bra prestanda för att möjliggöra hantering av multipla spektrala komponenter av motorexcitationen motsvarande snabba accelerationer.

Slutligen demonstreras hur bra isolering av motorvibrationer orsakade av transient motorexcitation, motsvarande t.ex. snabba bilaccelerationer inklusive växlingsförlopp, kan uppnås med samtidig hänsyn tagen till motorupphängningens olinjära karaktäristik. Detta åstadkoms genom utnyttjandet av bredbandig reglering baserad på tidsvarierande återkoppling av skattade tillstånd tillhörande en dynamisk störningsmodell. För att hantera motorupphängningens olinjära egenskaper presenteras en strategi för att generera analytiska linjära parameterberoende representationer av stora (med avseende på antalet frihetsgrader) olinjära system. En sådan representation utnyttjas för att säkerställa stabilitet hos det slutna systemet under stationära förhållanden samt i en studie av Lyapunov-stabilitet baserad på parameterberoende kvadratiska Lyapunovfunktioner. För att möjliggöra stabilitetsanalys härleddes en aiffin representa-
tion av det slutna systemet.

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