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Adaptive Multi Mode Vibration Control of Dynamically Loaded Flexible Structures

by

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Abstract

In this thesis, three control methodologies are proposed for suppressing multi-mode vibration in flexible structures. Controllers developed using these methods are designed to (i) be able to cope with large and sudden changes in the system's parameters, (ii) be robust to unmodelled dynamics, and (iii) have a fast transient response. In addition, the controllers are designed to employ a minimum number of sensor-actuator pairs, and yet pose a minimum computational demand so as to allow real-time implementation.

A cantilever beam with magnetically clamped loads is designed and constructed as the research vehicle for evaluation of the proposed controllers. Using this set-up, sudden and large dynamic variations of the beam loading can be tested, and the corresponding changes in the plant's parameters can be observed. Modal testing reveals that the first three modes of the plant are the most significant and need to be suppressed. It is also identified that the first and third modes are spaced more than a decade apart in frequency. The latter characteristic increases the difficulty of effectively controlling all three modes simultaneously using one controller. To overcome this problem, the resonant control method is chosen as the basis for the control methodologies discussed in this thesis.

The key advantage of resonant control is that it can be tuned to provide specific attenuation only at and immediately close to the resonant frequency of concern. Consequently, it does not cause control spillover to other modes owing to unmodeled dynamics. Because of these properties, a resonant controller

can be configured to form a parallel structure with the objective of targeting and cancelling multiple modes individually. This is possible regardless of the mode spacing. In addition, resonant control requires only a minimum number of collocated sensor-actuator pairs for multi-mode vibration cancellation. All these characteristics make resonant control a suitable candidate for multi-mode vibration cancellation of flexible structures.

Since a resonant controller provides negligible attenuation away from the natural frequencies that it has been specifically designed for, it is very sensitive to changes of a system's natural frequencies and becomes ineffective when these mode frequencies change. Hence, for the case of a dynamically loaded structure with consequent variations in mode frequencies, the resonant control method must be modified to allow tracking of system parameter changes. This consideration forms the theme of this thesis, which is to allow adaptive multi-mode vibration control of dynamically-loaded flexible structures. Three controller design methodologies based on the resonant control principle are consequently proposed and evaluated.

In the first approach, all possible loading conditions are assumed to be *a priori* known. Based on this assumption, a multi-model multi-mode resonant control (M^4RC) method is proposed. The basis of the M^4RC approach is that it comprises a bank of known loading models that are designed such that each model gives optimum attenuation for a particular loading condition. Conceptually, each model is implemented as a set of fixed-parameter controllers, one for each mode of concern. In reality, each mode controller is implemented as an adjustable resonant controller that is loaded with the fixed-model parameters of the corresponding mode. The M^4RC method takes advantage of the highly frequency-sensitive nature of resonant control to allow simple and rapid selection of the optimum controller. Identification of the set of resonant frequencies is implemented using a bank of band-pass filters that correspond to the mode frequencies of the known models. At each time interval a supervisor scheme determines for each mode which model has the closest frequency to the observed vibration frequency and switches the corresponding model controller output to attenuate the mode. Selection is handled on a mode-by-mode basis, such that for each mode the closest model is selected. The proposed M^{4}RC is relatively simple and less computationally complex compared to other multi-model methods reported in the literature. In particular, the M^{4}RC uses a simple supervisor scheme and requires only a single controller per mode. Other multi-model methods use more complex supervision schemes and require one controller per model. The M^{4}RC method is evaluated through both simulation and experimental studies. The results reveal that the proposed M^{4}RC is very effective for controlling multi-mode vibration of a flexible structure with known loading conditions, but is ineffective for unmodeled loading conditions.

In the second approach, the assumption that all loading conditions are *a priori* known is relaxed. An adaptive multi-mode resonant control (ARC) method is proposed to control the flexible structure for all possible (including unknown) loading conditions. On-line estimation of the structure's natural frequencies is used to update the adaptive resonant controller's parameters. The estimation of the natural frequencies is achieved using a parallel set of second-order recursive least-squares estimators, each of which is designed for a specific mode of concern. To optimise the estimation accuracy for each mode frequency, a different sampling rate suitable for that mode is used for the corresponding estimator. Simulation and experiment results show that the proposed adaptive method can achieve better performance, as measured by attenuation level, over its fixed-parameter counterpart for a range of unmodeled dynamics. The results also reveal that, for the same sequences of known loading changes, the transient responses of the ARC are slower than those of the M^{4}RC.

In the third approach, a hybrid multi-model and adaptive resonant control is utilized to improve the transient response of the ARC. The proposed multi-model multi-mode adaptive resonant control (M^4ARC) method is designed as a combination of the M^4RC and ARC methods. The basis of the proposed method is to use the M^4RC fixed-parameter model scheme to deal with transient conditions while the ARC adaptive parameter estimator is still in a state of fluctuation. Then, once the estimator has reached the vicinity of its steady-state, the adaptive model is switched in place of the fixed model to achieve optimum control of the unforeseen loading condition. Whenever a loading change is experienced, the simple M^4RC supervisor scheme is used to identify the closest model and to load the adjustable resonant controllers with the fixed parameters for that model. Meanwhile, the mode estimators developed for the ARC method are used to identify the exact plant parameters for the modes of concern. As soon as these parameters stop rapidly evolving and reach their steady-state, they are loaded into the respective adjustable controllers. The same process is repeated whenever a loading change occurs. Given the simplicity of the M^4ARC method and its minimal computation demand, it is easily applicable for real-time implementation. Simulation and experiment results show that the proposed M^4ARC outperforms both the ARC with respect to transient performance, and the M^4RC with respect to unmodeled loading conditions.

The outcomes of this thesis provide a basis for further development of the theory and application of active control for flexible structures with unforeseen configuration variations. Moreover, the basis for the proposed multi-model adaptive control can be used in other areas of control (not limited to vibration cancellation) where fast dynamic reconfiguration of the controller is necessary to accommodate structural changes and fluctuating external disturbances.

List of Abbreviations

ADC	Analog to Digital Converter
AIS	Adaptive Input Shaping
ARC	Adaptive Resonant Control
ARMAX	Auto Regressive Moving Average with eXternal input
ARX	Auto Regressive with eXternal input
BIBO	Bounded Input Bounded Output
BPF	Band Pass Filter
DAC	Digital to Analog Converter
FEM	Finite Element Method
FFT	Fast Fourier Transform
FRF	Frequency Response Function
HPF	High Pass Filter
IIR	Infinite Impulse Response
IMSC	Independent Modal Space Control
LHP	Left Half Plane
LPF	Low Pass Filter
M^4ARC	Multi-Model Multi-Mode Adaptive Resonant Control
M^4RC	Multi-Model Multi-Mode Resonant Control
MIMO	Multi Input Multi Output
MMAC	Multiple Model Adaptive Control
MMC	Multiple Model Control
MMSE	Minimum Mean Squares Error
MRAS	Model Reference Adaptive System
ODE	Ordinary Differential Equation
PDE	Partial Differential Equation
PLL	Phase Locked Loop
PPF	Positive Position Feedback
RLS	Recursive Least Squares
SDOF	Single Degree of Freedom
SISO	Single Input Single Output
STR	Self Tuning Regulator

Certification

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

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Adelaide, 26 July 2006

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Publications in Support of the Thesis

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2. Tjahyadi, H., He, F., and Sammut, K. Vibration control of a cantilever beam using adaptive resonant control. In *Proceedings of the 5th Asian Control Conference ASCC2004* (Melbourne, Australia, July 2004), pp. 1786-1790.

3. Tjahyadi, H., He, F., and Sammut, K. Vibration control of a cantilever beam using multiple model adaptive resonant control. In *Proceedings of IFAC Workshop on Adaptation and Learning in Control and Signal Processing (ALCOSP04)*(Yokohama, Japan, September 2004), pp. 409-413.

4. Tjahyadi, H., He, F., and Sammut, K. Multi-mode vibration control of a flexible cantilever beam using adaptive resonant control. *Smart Materials and Structures*, 15:270-278, 2006.

5. Tjahyadi, H., He, F., and Sammut, K. M^{4}ARC: Multi-Model-Multi-Mode Adaptive Resonant Control for Dynamically-Loaded Flexible Beam Struc-

tures. In preparation to be submitted to *IEEE Trans. Control Systems Technology*