ACTIVE VIBRATION REGULATION OF A CONVERTIBLE VEHICLE USING SYSTEM IDENTIFICATION

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Abstract
This paper describes an approach towards the development of an active vibration regulation (AVR) system on a convertible car equipped with a hydraulic actuation system and fully instrumented to measure certain positions and accelerations. As a discrete-time black-box system identification technique, experimental modal analysis is used to identify a model from the measured dynamic response of the car body and the hydraulic actuators. The AVR system in the presence of process and measurement uncertainties is designed with the aim of attenuating the amplitude of the first eigenmode of the system considered. The AVR algorithms are digitally implemented and real-time experiments involving a hydro-pulse four poster rig are conducted. The results from these are evaluated and it is shown that the AVR system achieves a significant vibration reduction in the first eigenmode, which is important for riding comfort.

1 Introduction
Road imperfections, aggressive driving and disturbances caused by the engine are some causes of vibration phenomena that have a lasting impact on the driving comfort of a vehicle [1]. In particular, when a convertible (a car without a solid roof) is subjected to disturbances, the reduced flexural stiffness of the car body may cause vibrations which can result in poor riding comfort. These vibrations are low frequency oscillations at the first resonance frequencies of the car body [2].

Passive regulation methods, which involve the use of reactive or resistive devices such as vibration dampers and dynamic absorbers that either load the transmission path of the disturbing vibration or absorb vibrational energy, are efficient at single low-frequency oscillations, but expensive and unwieldy when considering broadband regulation of flexible structures, particularly with respect to reducing the fuel consumption of motorised vehicles, which is of paramount interest to the automotive industry nowadays [3]. As a consequence, in a number of practical fields it has been shown that active vibration regulation (AVR) systems can serve as an attractive alternative, which overcomes these limitations and makes a substantial contribution to improving driving comfort [4].
Nevertheless, it would appear that little work has been carried out in attempts to enhance and improve the in-vehicle comfort in convertible vehicles. This is the motivation for this study and this paper is an experimental investigation into an AVR system on a convertible car equipped with a hydraulic actuation system and fully instrumented to measure displacements and accelerations.

Supporting experimental work to this study carried out by Wilhelm Karmann GmbH in Germany considered the integration of hydraulic actuators in the rear cross-sets of a convertible vehicle ensuring that the first torsional vibration transmission path was accounted for. Based on this the following objectives fall within the scope of this study:

1) Experimental modal analysis to identify a model from the measured dynamic response of the car body comprising the hydraulic actuators;

2) Design of an optimal AVR system in the presence of process and measurement uncertainties aiming at attenuating the amplitude of the first eigenmode of the system considered; and

3) Digital implementation of the AVR algorithms for real-time experimentation involving a hydro-pulse four poster rig replicating differing road conditions.

2 System Modelling

As can be seen from Figure 1, the active elements are placed between the rear cross-sets of the test vehicle and involve the use of such components as servo valves, pressure and displacement sensors, etc. The accelerometers provide the regulator with input signals, whereas the output signals from the regulator are forwarded to the hydraulic actuators for AVR.

The design of an AVR system meeting certain performance requirements is facilitated by the availability of mathematical models to be regulated. Consequently, experimental modal analysis is
considered, providing a means for identifying modal parameters such as eigenfrequencies, eigenmode shapes and damping coefficients.

Furthermore, the construction of a model from the input-output data recorded involves the use of a set of candidate models [5]. Within the scope of this study, an auto-Regression with exogenous variables (ARX) model with some unknown physical parameters is constructed from basic physical laws. As a basic approach to the assessment of the quality of the model the least mean squares method (LMS) is used.

2.1 Experimental Modal Analysis

Experimental modal analysis has been shown to be an effective method of studying structural dynamic characteristics by obtaining a set of frequency response functions [6]. The test rig, as shown in Figure 2, consists of a convertible vehicle equipped with the hydraulic actuation system and fully instrumented to measure certain positions and accelerations at a number of points. A hydro-pulse four poster rig replicating different road conditions is used as the exciter. An additional data acquisition system is also available to log the dynamic behaviour of the system.

Using the above experimental setup, the vehicle was excited by a band-limited, random vibration of the wheels in the frequency range of 1 to 45Hz with small amplitudes (±10mm). This guarantees a persistent excitation allowing for the first eigenmode to form accurately. The measurements were collected at a sampling rate of 1550Hz for 170sec.

As can be seen from Figure 3, which shows the realisation of the experimental setup for analysing the active elements, a similar approach is considered to investigate the behaviour of the hydraulic actuators of the AVR system. They were excited by a swept sinusoidal signal of frequency varying from 1 to 30Hz in a sweep time of 170sec. Again, the measurements were collected at a sampling rate of 1550Hz for 170sec.
The results from the experiments that aim at identifying the vibrational behaviour of the car body are given in Figure 4. Furthermore, the open-loop bode diagrams for the transfer functions from the voltage applied to the servo valves of the AVR system actuators to the acceleration measured at the A-column are plotted in Figures 5 and 6.

It is apparent that the convertible has a serious torsional resonance in the frequency range considered, which is not present in standard vehicles. As expected, this maximum amplitude of vibration corresponding to this first eigenmode of the system is measured at the A-column. It should be mentioned that closing the hood of the convertible vehicle results in an increase of 1Hz of the first eigenmode.

**Figure 4** The convertible (— — —) has a torsional resonance at 14Hz, which is not present in standard vehicles (———).
Figure 5 Bode diagrams for the transfer functions from voltage applied to the servo valve of the left active element (in $x$-direction) to acceleration measured at the A-column: (a) hood open; (b) hood closed.

Figure 6 Bode diagrams for the transfer functions from voltage applied to the servo valve of the right active element (in $x$-direction) to acceleration measured at the A-column: (a) hood open; (b) hood closed.

2.2 System Identification

On the basis of the input-output data recorded during the experiments a linear model was constructed according to [5],

$$A(z^{-1})y(kT) = B(z^{-1})u(kT) + C(z^{-1})z(kT),$$

where

$$A(z^{-1}) = 1 + a_1 z^{-1} + \ldots + a_{na} z^{-na},$$

$$B(z^{-1}) = b_0 + b_1 z^{-1} + \ldots + b_{nb} z^{-nb},$$

$$C(z^{-1}) = 1 + c_1 z^{-1} + \ldots + c_{nc} z^{-nc}. $$
The three variables constituting the transfer function model in Eq. (1) are the measured output of the process \( y(kT) \), the known (or measured) input to the process \( u(kT) \) and the noise or uncertainty in the model \( z(kT) \), which is assumed to be a stationary, zero-mean, Gaussian white noise process with constant power spectrum, as stated before. Using Eqs. (2), Eq. (1) may be put in the form:

\[
y(kT) = m^T(kT)\Theta + z(kT),
\]

with

\[
m^T(kT) = \begin{pmatrix} -y(kT-T) & \ldots & -y(kT-na) & u(kT) & \ldots & u(kT-nb) & z(kT-T) & \ldots & z(kT-nc) \end{pmatrix},
\]

and the parameter vector,

\[
\Theta^T = (a_1 \ldots a_{na} b_0 \ldots b_{nb} c_1 \ldots c_{nc}).
\]

Within the scope of this study, an ARX model is considered, i.e. \( nc=0 \):

\[
A(z^{-1})y(kT) = B(z^{-1})u(kT) + z(kT).
\]

Accordingly, the parameter vector in Eq. (5) simplifies to,

\[
\Theta^T = (a_1 \ldots a_{na} b_0 \ldots b_{nb}).
\]

Therefore, the identification procedure predominantly involves estimating these parameters. In this paper the LMS method is used to achieve this objective, and a number of state space models are obtained, which accurately capture the dynamics of the vehicle as well as the actuators with a fit of approximately 90%.

### 3 Optimal Feedback Regulation in the Presence of Uncertainty

The AVR system is provided by the solution of an extended optimal regulation problem in modal space, where white noise disturbance inputs are included and incomplete state measurements can be used to construct the full state vector through computing the appropriate estimator gain, namely Kalman filter gain.

The inputs to the vehicle correspond to an environmental disturbance signal composed of random excitation of the wheels, harmonic excitation from the engine and the actuating signals, as can be seen from Figure 7. The output is the noisy signal measured by the accelerometer at the A-column only. This leads to an augmented system including the state space models of the hydraulic actuators, which, in turn, is used to solve for the filter algebraic Riccati equation and the regulator algebraic Riccati equation in order to obtain the Kalman gain and the state-feedback gain, respectively.

![Figure 7 Schematic diagram of the vehicle illustrating the location of the sensors and actuators in the context of AVR.](image-url)
4 Experimental Investigations

Encouraged by the results obtained from preliminary simulation studies, the regulator and estimator algorithms are programmed using MATLAB/Simulink® and implemented in the data acquisition and control board dSPACE® DS1401 for further experimental investigations. A schematic of the experimental test rig is shown in Figure 8.

![Figure 8: Realisation of the experimental test rig for assessing the AVR system under real-time conditions.](image)

In Figure 9 the measured frequency response functions of the vehicle are depicted. As a result of the vibration regulation the peaks at the first resonances (hood closed: 15Hz; hood open: 14Hz) of
the eigenmodes are reduced by 50%. Additionally, the resonances are slightly shifted to higher frequencies due to the presence of the AVR system.

5 Concluding Remarks and Further Developments

In this paper, an active vibration regulation (AVR) scheme has been designed and implemented to suppress the vibration amplitude of the first torsional eigenmode of a convertible vehicle subjected to random road inputs and harmonic engine excitations. The most appropriate modal basis has been found for determining the AVR system through system identification. This has been designed by means of optimal regulation theory in the presence of process and measurement uncertainties aiming at minimising the vibration amplitude of the eigenmode considered.

The AVR system has achieved a significant vibration reduction in the first eigenmode (torsional vibration of the car body), which is important for riding comfort. Consequently, it has been concluded that the use of active regulation is an effective way to attenuate undesired vibrations of such flexible structures as car bodies.

By utilising a regulator designed on the basis of an experimentally approximated, truncated model including a single eigenmode only, spill-over inevitably occurs. Moreover, since the majority of dynamic characteristics regarding motorised vehicles are poorly known in real-life and large as well as unpredictable variations do occur, a comprehensive solution needs to be proposed in order to make a regulation system adaptive. With this in mind, more effort devoted to the dynamic model reduction of distributed structures and to the development of adaptive regulation algorithms is required.

This has already established the future direction for investigation towards developing novel model reduction techniques on the basis of a full-car finite element model and the utilisation of adaptive regulation schemes, particularly with respect to their applicability to automobile systems.

6 References


