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Adaptive Modeling of Vehicle Mirror Vibrations by Predictive Compensation

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Abstract
The external and internal mirrors used particularly in high mass recreational and commercial vehicles are prone to vibrations. Under certain conditions, this leads to blurring of the reflected images above the tolerable levels for the human vision. While such vibrations are quite disturbing, they can compromise the driver’s safety on the road. An adaptive predictive system is designed to compensate for the mirror vibrations under different driving conditions. The realtime adaptive modeling of the vibrations using ARMA for the purpose of their prediction is reported.

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Adaptive Modeling of Vehicle Mirror Vibrations by Predictive Compensation

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Abstract

The external and internal mirrors used particularly in high mass recreational and commercial vehicles are prone to vibrations. Under certain conditions, this leads to blurring of the reflected images above the tolerable levels for the human vision. While such vibrations are quite disturbing, they can compromise the driver’s safety on the road. An adaptive predictive system is designed to compensate for the mirror vibrations under different driving conditions. The real-time adaptive modeling of the vibrations using ARMA for the purpose of their prediction is reported.

1. Introduction

The external and internal mirrors used particularly in high mass recreational and commercial vehicles are prone to vibrations due to various factors such as large size of the mirror, wind and road surface roughness. The vibration can lead in certain conditions to blurring of the reflected images above tolerable levels for the human vision. Hence, it is quite disturbing for the driver, and in certain conditions becomes a safety hazard.

Although the rear-view mirrors’ structural vibration characteristics have been optimised, and in particular their weights have been greatly diminished, the problem is still present. Previous attempts using both passive damping and active vibration control have been unsuccessful at overcoming the resonant modes in particular. Therefore an intelligent vibration controller is required to maintain a sharp reflected image in the mirror under all driving conditions.

The approach employed in this work is based on an adaptive control scheme, performed by dynamically tuning the controller’s parametric predictive model. A signal is generated to drive the actuators, which in turn rotate the surface of the mirror in such a way that vibrations are not perceptible.

2. Background

The focus of a significant number of previous works in this area has been on optimising the rear view mirrors mechanical structure based on Computer Aided Design tools [1,2]. Finite element analysis (FEA) techniques have been used thoroughly to optimise the shape and stiffness of mirrors to reduce vibration. Another approach employed has been Computer Aided Fluid Dynamics through which the flow patterns and pressure distribution around a mirror are studied [3]. The results are combined with those of FEA to extract the mirror response frequency. The
baseline designs of mirrors are consequently modified to minimise the dominant vibration modes.

![Simulated blurring of a mirror mounted on a shaker](image1)

### Figure 1 - Simulated blurring of a mirror mounted on a shaker

Further statistical methods have been applied to increase the robustness of the mirror optimization process [4]. Within constraints of cost and manufacturing, the state of the art in design and manufacturing of car mirrors seems to have reached a relatively high level. Consequently the weight of the rear-view mirror has been greatly diminished and its structural characteristics have been optimized.

The issue of vibration of the mirror, however, is still outstanding and requires further work.

There are two patents which specifically address vibration damping in side-view mirrors, and internal rear-view mirror featuring day/night position [5, 6]. The method proposes a passive vibration compensator. The vibration dampers or stabilizers are mounted on the pivotally adjustable reflective mirror subassembly.

The concept of using active compensation to remove vibration in mirror systems has also been addressed to some extent in the literature [7]. Experimentation was first undertaken to quantify the vibration threshold of the human perception. In parallel, tests were conducted to reveal the actual vibration of the mirror on the truck. The comparison of those two frequency responses has shown that perception was the most affected by frequencies in the range of [0.40Hz].

Furthermore, three control algorithms, namely PID control, optimal control and adaptive feedback were applied to the model of the mirror through computer simulation. The adaptive method was based on filtered-X-least mean square (FXLMS) algorithm. All the models used in the feedback controllers were developed offline. Yet, the limits of robustness of such models have been observed. The methods have shown poor tolerance not only to plant variations but also to the external dynamic variations affecting the mirror system.

### 3. Vibration Characteristics

The measured vibration of the mirror surface is the result of two major vibrations of the mirror assembly systems. One is the rotation and translation of the mirror surface around and relative to its axes and the other is the displacement of the mirror itself including the mirror housing, the mirror arm and the mirror bracket relative.

The vibration of the mirror itself consists of four components (Fig. 3):

![Fundamental movements of a mirror under driving conditions](image2)

### Figure 3 - Fundamental movements of a mirror under driving conditions

1. rotation around the axis perpendicular to the mirror surface
2. displacements parallel to its surface
3. the transition displacement
4. the rotation around the vertical and horizontal axes

The motions (1) and (2) do not affect the location of the image as seen by the driver. However in the other two cases the image moves forward and backward parallel to the perpendicular of its axis and will cause noticeable shifting of the reflected image. The active
control of the vibration in the mirror primarily can remove the rotational movement. According to the studies conducted in Ref. [8, 9] the aerodynamics of the vehicle are the main cause of vibration for frequencies above 20Hz. Frequencies below this value are mainly attributed to the car body vibration. The control system should, however, respond to all frequencies in the range [0-120Hz] with special emphasis on the resonant modes.

4. Adaptive Predictive Approach

In order to suppress the vibrations occurring in a moving vehicle’s mirrors, a hybrid predictive Active Vibration Control (AVC) system is presented. The method is hybrid in that it combines both passive and active ways to compensate for the different sources and types of vibration. Besides the optimisation of the mechanical structure and use of frictional dampers between the glass and the bracket, the effort is put on the electronic part to suppress the most significant part of the vibrations at minimal cost.

The controller generates a signal utilised to cancel out the oscillation using superposition technique. The model used by the controller is based on the structural response of the mirror assembly structure to the vibrations. Furthermore, the method is predictive as there is always a delay between the measurement of the vibration signal and the generated control signal. Therefore it is essential to predict the future amplitude value of the vibration. The minimum prediction horizon necessary correspond to the overall loop delay required for signal processing - i.e analogue-to-digital conversion, digital processing, digital-to-analogue conversion of the signal and actuator response time.

The predictive controller calculates the most likely value of the vibration signal for the next future interval and generates a control signal for the actuators accordingly. Although a 100% match for a stochastic signal cannot be met by any predictive method, some residual vibration due to prediction errors is acceptable when kept under a certain level. Passive damping plays the role of minimising those attenuated vibrations further more.

Mathematically, the vibration waveforms are a combination of various frequencies and magnitude of vibration which depend on the external conditions. These factors include wind velocity and direction, engine regime, road surface roughness and hence are neither predictable nor practically measurable. Therefore it is necessary to dynamically tune the controller in order to obtain the necessary compensation efficiency.

An adaptive algorithm is incorporated to enhance the accuracy of the prediction model dynamically. It uses the measured error between the actual vibration signal and predicted signal. The predictive model is optimized for performance and computational requirements.

The P131 (Fig.2) model mirrors are used to conduct the experiments. The structural response of the mirror to the vibration is measured using accelerometers placed on the glass surface. The overall efficiency of the system is assessed according to the human perception threshold of mirror vibration. However, both the approach and the algorithms developed are kept generic. It is envisaged that the developed controller can be applied to other mirror systems with minimum effort.

5. On-road Measurements

A series of experiments were conducted to measure the mirror vibrations caused by various factors in a moving vehicle. A data logging system was installed in a Ford F250. Three accelerometers were placed on the surface of the P131 mirror. The vehicle was driven on highway, dirt road, and speed bumps, at constant speed or with positive or negative acceleration, turning, and with the mirror’s arm extended or retracted. A database of typical mirror vibration signals was built and is later used to test and validate the adaptive predictive compensation algorithms.

The results showed that the power spectrum of the vibration signals exhibited several frequency peaks (Fig. 4), varying between 20 and 100 Hz, and depending on the driving conditions.

Furthermore, the vibration patterns were analysed for periodicity. It was found that the signal could appear as relatively cyclic but only over very limited segments of time. As a consequence, developing a compensation strategy using this property, which could have many advantages, cannot be considered. Instead a more generic approach to time series prediction was used, as described later in this paper.
6. ARIMA - Predictive Model of Vibration

The purpose of the prediction algorithm is to forecast, in real time, the values of the vibration signal. It is an essential condition that the prediction horizon be equal or superior to the overall delay of the feedback loop. This delay was measured on a custom built experimental rig using a measurement approach similar to Ref. [10]. The loop delay was found to be approximately 1ms.

Auto Regressive Integrated Moving Average (ARIMA) was used to model the mirror vibration patterns. This particular tool was selected for its accuracy and the well-defined development methodology for identification, estimation and validation of the models. The model provides an estimate of the future values of a signal based on the past measured values and prediction errors.

There should exist an optimum sampling rate with respect to accuracy under which the model operates. Depending on the rate at which the vibration signal is sampled, the ARIMA model has to predict one to several samples ahead in order to reach the 1ms-ahead horizon. Higher sampling rate lead to better accuracy of the measured signal for the range of useful frequencies [0-120]Hz but more steps ahead, hence less predictive accuracy. The study of the process at different rates showed that a system sampling at 1KHz (1 sample-ahead for 1ms) would produce a satisfying trade-off.

The degree of complexity of the model is defined by two constants that constitute the order. The latter defines a compromise between prediction accuracy and computational load. The order is conventionally pre-determined by calculating auto-correlation function (ACF) and Partial ACF of the data which is an approximate method. In this work however, a different approach was adopted. Initially, all the ARIMA models of order [p, 1, q] for all combinations of p and q varying between {1, 10} were calculated. The selection of the most adequate model was achieved by estimating both the Akaikes Information Criterion (AIC) and Final Prediction Error (FPE) for each model.

This method of calculating the static ARIMA model was implemented using vibration signals from the database. It was found that for a variety of on-road signals a model of order [4, 1, 4] provided the best overall predictive performance while maintaining a satisfying computational efficiency.

However, vibration patterns change constantly due to road conditions, wind and engine regime. Hence it requires the internal parameters of the ARIMA model to change accordingly.

7. Recursive ARIMA Algorithm

The primary goal pursued in the modeling is to maintain a high level of accuracy in the predictions under all the driving conditions. The recursive ARIMA algorithm adapts the prediction model in real time to the changes in the vibration pattern. In the algorithm applied, eight parameters of the ARIMA[4, 1, 4] model are estimated at every sample time.

A set of 4 ARIMA recursive algorithms were tested offline in order to compare their accuracy in predicting the typical vibration patterns observed on the P131 mirror.

- Forgetting factor (FF) approach
- Un-normalized gradient (UG) approach
- Normalized gradient (NG) approach
- Kalman filter (KF) approach

These methods operate by calculating a gradient with respect to the goodness of the fit at the current time. They differ from one another in the way the gradient is calculated.

The norm:
\[
\sqrt{\sum_i a_i^2}
\]

with
\[i \in [1, \text{segment \_length}]\]
and
\[a_i = \text{reference},(t) - \text{predicted},(t - 1)\]

was used as an index to compare the accuracy of the algorithms.

The four approaches were applied to 16 representative segments of 10 seconds of vibration.
data. Each algorithm was individually and extensively tuned by varying its internal parameters.

For each segment of data, an ideal reference signal was created by filtering the measured signal through a low pass linear phase FIR of order 100 and cut off frequency 120Hz. It was then shifted back in time by the corresponding delay introduced by the filter. The resulting time series contained only the pertinent frequency information [0-120] Hz and constituted a signal close to the ideal predicted signal.

7.1. Results

A total of 400 cases were computed, leading to a large number of performance ratings. Tables 1 to 4 show the results obtained in the case of vibrations observed on a dirt road at 40kph. A systematic analysis of the results showed that the NG and UG algorithms perform consistently better than the two other. NG was selected as it outperforms UG in 60% of the cases. However depending on the driving conditions, the best results are obtained while the normalized gradient internal gain parameter varies between 0.00025 and 0.001. Since the purpose of the system is to compensate for the most disturbing vibrations, a weighted average of the latter parameter was calculated, emphasizing by a factor 2 the cases where vibrations have the most significant amplitude (highway and dirt road). The normalized gradient algorithm parameter was therefore found to be optimum for a value of 0.0006.

Using the above results a theoretical attenuation of the vibration of 17dB on average is achieved.

Table 1. Goodness of fit for varying forgetting factor

<table>
<thead>
<tr>
<th>λ Factor</th>
<th>Norm</th>
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<tbody>
<tr>
<td>0.980</td>
<td>17.309</td>
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<tr>
<td>0.995</td>
<td>15.242</td>
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<tr>
<td>0.996</td>
<td>15.488</td>
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<tr>
<td>0.997</td>
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<tr>
<td>0.998</td>
<td>15.187</td>
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<tr>
<td>0.999</td>
<td>15.976</td>
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Table 2. Goodness of fit for varying kalman filter factor

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<td>0.001</td>
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<td>0.005</td>
<td>17.187</td>
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Table 3. Goodness of fit for varying normalised gradient factor

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Table 4. Goodness of fit for varying un-normalised gradient factor

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<th>Norm</th>
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8. Conclusion

A novel approach to compensating vibration in vehicle mirrors was conceptually defined and a background review conducted. The nature of the vibrations in the mirror was studied. As a result, a rig was successfully built and used to measure some critical parameters, which in turn are used in the development of the prediction algorithm. ARIMA modeling was studied as the core prediction tool.

A method for determining, calculating and selecting an optimum adaptive predictive model for the compensation for vibration under varying conditions was developed. It was tested on vibrations signals measured directly on-road. The model can successfully predict vibrations in a mirror for its compensation. It was found that the model based on the normalized gradient recursive ARIMA algorithm gives the best prediction and real-time adaptability. It was tested for a prediction horizon of 1ms, and yields an average theoretical attenuation of 17dB.

Further work is carried to improve the overall prediction accuracy by pre-filtering of the vibration signal. The optimum trade-off between the filtering delay introduced and the gain in accuracy remains to be studied.

10. References


11. Acknowledgment

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