

MODELING AND PREDICTION OF STOCHASTIC VIBRATIONS IN TRAIN OPTICAL DETECTION SYSTEMS

Ivan PAVLOVIĆ¹ [0000-0003-0062-4342]Nikola DESPENIĆ² [0000-0002-4387-1688]Milan BANIĆ³ [0000-0001-8684-042X]

Abstract This paper presents a stochastic modeling approach for optical detection systems employing viscoelastic stabilizers. In order to develop an adequate vibration model, experimental results obtained from dynamic testing of a viscoelastic optical detection system mounted on a railway vehicle were used. The conducted tests evaluated the effectiveness of viscoelastic vibration suppression in a railway optical detection system whose primary objective is to stabilize the captured image and reduce potential errors in system decision-making. The tested viscoelastic stabilizer is represented using the Voigt–Kelvin model, whose parameters are optimized based on experimental measurements obtained under real-time operating conditions of the optical detection system. The system response is further analyzed under a real noise stochastic process used to represent the external excitation load.

Keywords – Stochastic model, viscoelastic suppression, Voigt-Kelvin model, railway optical detection system, real noise process.

1. INTRODUCTION

The stabilization of optical systems is essential in applications such as astronomy, optical communications, laser systems, and medical imaging, where image quality must be preserved under vibrations, thermal variations, and other environmental disturbances. Numerous studies have addressed this challenge using advanced modeling and control approaches, including modern design methodologies for mitigating turbulence, structural vibrations, and thermal effects [1], as well as adaptive filtering techniques, such as Kalman-based algorithms, for reducing noise and improving image correction performance [2].

Among available solutions, viscoelastic stabilization represents an effective passive approach for vibration suppression. The incorporation of viscoelastic layers between optical components and their supporting structure reduces resonant amplitudes and enhances overall dynamic stability [3-5]. Within the H2020 SMART project [6], an optical detection system (ODS) for freight vehicles was developed, incorporating a dedicated passive isolation system to attenuate vibrations induced by vehicle motion. The dynamic behavior of such systems has been further investigated in [7].

2. OBSERVED SYSTEM

The optical detection system (ODS) is installed on a freight locomotive and comprises three RGB cameras, a thermal imaging camera, a night-vision camera, and a 3D laser scanner (LiDAR). All sensing components are integrated within a specially designed protective enclosure. The enclosure is mounted on a structural plate rigidly attached to the locomotive (Fig.1) carbody beneath the front headlights, resulting in direct structural coupling with the vehicle.



Fig. 1. The SMART ODS prototype mounted on

¹ Faculty of Mechanical Engineering, University of Niš, A. Medvedeva 14, Niš, Serbia, ivan.pavlovic@masfak.ni.ac.rs

² Faculty of Mechanical Engineering, University of Niš, A. Medvedeva 14, Niš, Serbia, nikola.despenic@masfak.ni.ac.rs

³ Faculty of Mechanical Engineering, University of Niš, A. Medvedeva 14, Niš, Serbia, milan.banic@masfak.ni.ac.rs 21

locomotive

Due to the rigid connection between the mounting plate and the locomotive structure, dynamic loads arising from wheel-rail interaction, track irregularities, and structural vibrations are directly transmitted to the enclosure and the embedded vision sensors. To reduce vibration transmissibility and mitigate the effects of broadband stochastic excitations and transient shocks, a passive vibration isolation system based on viscoelastic elements was designed and implemented, as shown in Fig. 2.



Fig. 2. Viscoelastic elements for vibration suppression

Vibration responses were recorded using two triaxial inertial measurement units (IMUs), installed on the mounting plate and inside the ODS enclosure (Fig. 3) presents viscoelastic system for which the Voigt-Kelvin vibration model is suggested.

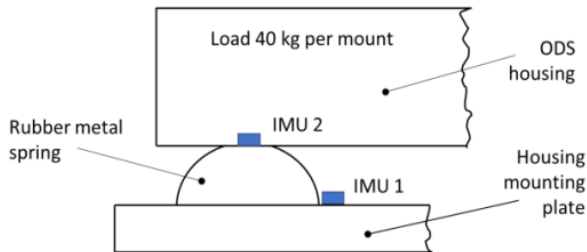


Fig. 3. Positioning of IMU's on the housing mounting plate and inside the ODS housing

The performance of the isolation system was evaluated during operational train runs at speeds ranging from 20 to 80 km/h on a straight track section. Acceleration measurements were conducted in the vertical direction at two locations: on the mounting plate rigidly attached to the carbody and inside the sensor enclosure. This direction was treated as the most important one, since the largest disturbance levels and the most pronounced dynamic effects were observed in the vertical axis. For this reason, the vertical response was taken as the primary indicator of the effectiveness of the proposed isolation concept. Based on the measured vertical accelerations shown in Fig. 4, the stochastic force acting on the ODS was

recalculated and used as the input for further dynamic optimization.

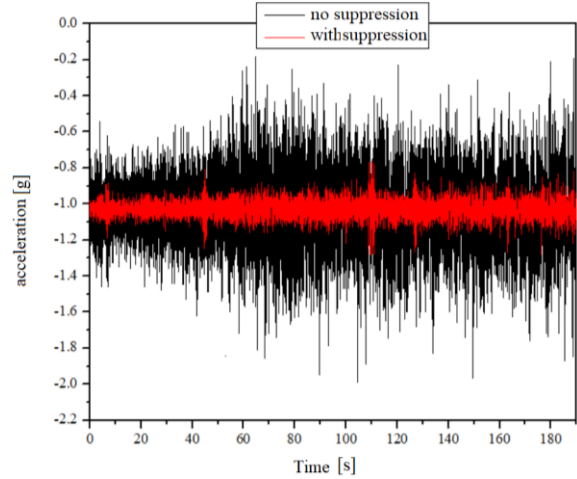


Fig. 3. Experimental measurements in vertical direction

This approach made it possible to evaluate the transmissibility of vibrations through the mounting structure and to assess how efficiently the viscoelastic elements reduce the excitation transferred to the optical detection system under realistic operating conditions.

3. VIBRATION MODEL OPTIMIZATION

According to the viscoelastic system described for stabilising the ODS system in the previous section, the viscoelastic Voigt-Kelvin model [8] is applied to model and analyse camera stochastic vibrations. This model is one of the basic linear approaches for describing materials that simultaneously exhibit elastic and viscous properties, with an elastic spring and a viscous damper connected in parallel to represent the stress-strain relationship.

$$F(t) = c \cdot x(t) + b \cdot dx(t)/dt + m \cdot d^2x(t)/dt^2, \quad (1)$$

where c is the spring stiffness, b is damping coefficient, m is the mass of analyzed system.

For the initial Voigt-Kelvin model parameter identification the global optimization method Differential Evolution was employed.

The parameters b and c of the Voigt model were optimized by defining an objective function aimed at minimizing the deviation between the experimentally measured output acceleration and the corresponding model response. Initially, the optimization procedure was based on direct fitting of the complete time-domain signal. However, this approach did not provide a satisfactory correlation between the experimental data and the simulated response, particularly in terms of accurately reproducing the dynamic characteristics of the measured signal over the entire observation interval.

To improve the robustness of the parameter identification process, the optimization criterion was

further modified so that the model primarily reproduces the amplitude range of the response. In this context, special emphasis was placed on matching the minimum and maximum acceleration values, as well as the standard deviation of the experimental signal, which was used as an indicator of the overall variability and energy content of the response. Such an approach enabled a more stable and physically meaningful identification of the model parameters, despite the simplicity of the employed constitutive representation. Figure 5 shows that the optimized Voigt-Kelvin model provides a good agreement with the experimentally observed accelerations amplitudes by matching both the minimum and maximum response levels of the system, which indicates that the identified stiffness and damping parameters capture the dominant dynamic behavior of the viscoelastic mount under service conditions.

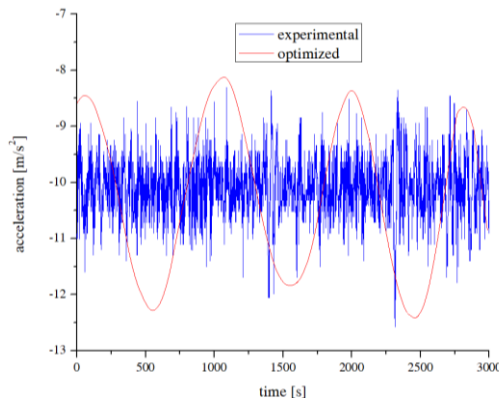


Fig. 5. Optimization results: $c=9.02$ N/m and $b=0.096$ Ns/m

4. STOCHASTIC RESPONSE UNDER REAL NOISE EXCITATION

According to Voigt-Kelvin model given with expression (1) the adequate simulation scheme is constructed (Fig 6).

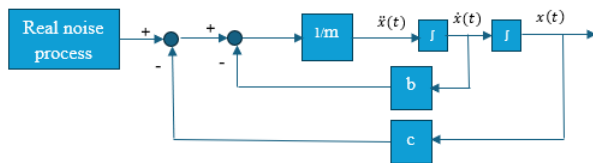


Fig. 6. Simulation scheme of Voigt-Kelvin model given by expression (1)

Now, the system response is tested when input stochastic force in simulation is modeled by real noise process.

The real noise process is given by the one-dimensional Itô-type stochastic differential equation

$$dX(t) = \alpha * X(t) * dt + \sigma * dW(t), \quad (2)$$

where α and σ are constants and $W(t)$ is the standard Wiener process.

Real noise process is a random signal characterized by broadband, irregular fluctuations with statistical

properties derived from measured or observed data, making it more complex than idealized noise models such as white or colored noise. In system analysis, it is often used to model actual environmental or operational forces acting on a structure, such as the vibration induced forces on an optical detection system mounted on a moving vehicle. By representing the force as a stochastic real noise process, researchers can more accurately simulate the system's dynamic response under realistic, unpredictable excitations and evaluate the effectiveness of stabilization or damping strategies, such as viscoelastic isolation, under real world conditions. Modeling and simulation of this process using MATLAB software is detailed in previous authors work [9].

Figures 7 and 8 illustrate how the Voigt-Kelvin model responds under a real noise excitation when the model parameters are varied, showing that both stiffness and damping coefficient significantly influence the amplitude and character of the predicted vibration response.

In Figure 7, changes in the damping coefficient mainly affect the rate of energy dissipation, with higher damping reducing oscillation intensity and producing a more stable response, which confirms the expected role of viscous resistance in limiting vibration transmission.

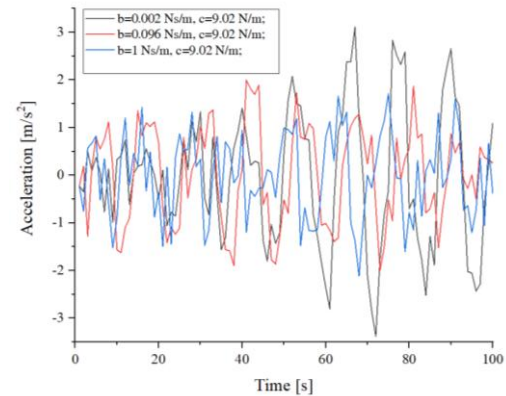


Fig. 7. Voigt-Kelvin model response for different values of damping coefficient b under real noise process

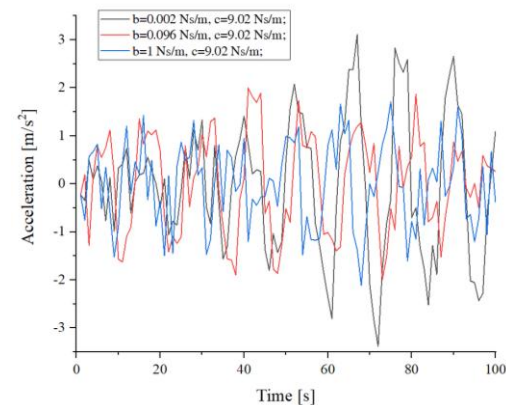


Fig. 8. Voigt-Kelvin model response for different values of spring stiffness c under real noise process

In Figure 8, variation of the spring stiffness alters the overall rigidity of the system, so that higher stiffness tends to increase the transmitted dynamic force and reduce the isolation effect, while lower stiffness improves vibration attenuation but may also lead to a softer system response. Taken together, the two figures demonstrate that the optimized model is sensitive to parameter selection and that a balanced combination of stiffness and damping is necessary to achieve effective stabilization under stochastic excitation.

5. CONCLUSION

The performed analysis confirms that the passive vibration isolation system effectively reduces the transmission of railway induced vibrations to the optical detection system mounted on the train body. Experimental results demonstrate that the selected rubber-metal mounts provide substantial attenuation of vibrations in vertical direction, thereby improving the operational stability of the sensor housing under real service conditions.

In addition to the experimentally confirmed isolation performance, the Voigt-Kelvin viscoelastic model proved to be a useful simplified analytical representation of the stabilized system. After parameter optimization based on measured acceleration data, the model offers a physically meaningful description of the spring-damper behavior and can be efficiently applied for preliminary evaluation of system response, sensitivity analysis, and design refinement.

Further testing of the optimized model under real stochastic excitation shows that it can also be employed as a force-input representation of the acting noise process for different levels of disturbance and model parameters. In this way, the model supports the analysis of stabilization effectiveness under realistic non-deterministic loading and provides a practical framework for assessing the robustness of the optical detection system.

Although the Voigt-Kelvin model does not fully reproduce the measured dynamic response with the accuracy of more complex viscoelastic formulations, its simplicity, interpretability, and computational efficiency make it valuable for stabilization oriented design and optimization. It is therefore suitable as an intermediate modeling tool between experimental assessment and higher order constitutive analysis. Overall, the combined experimental and numerical results confirm that the proposed isolation concept

improves the dynamic conditions required for reliable optical sensing in railway applications. The optimized Voigt-Kelvin model adds further value by enabling fast evaluation of stabilization performance under stochastic excitation and by supporting future development of vibration isolated vision based systems.

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