Analysis of transient phenomena in automotive vehicle suspension dampers

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Abstract. An automotive damper is a mature technology in the industry. From an engineering standpoint, the device design is a compromise between handling characteristics of a car, passenger comfort and safety, NVH and durability. Recently, new automotive trends in vehicle chassis design have generated research and engineering efforts. The engine and powertrain vibration reduction, the entry of hybrid/electric vehicles have caused all vibration sources due to vehicle chassis operation recognizable by both driver and passengers. Moreover, due to the increasing structural stiffness requirements imposed by vehicle OEMs (Original Vehicle Manufacturer) the energy dissipation efficiency of the damper has become a research and engineering challenge. It is, therefore, vital to propose means for eliminating or reducing their influence through changes that will result in vibration level reduction and techniques methods, metrics for evaluating them. In the dampers any disturbances in force generation translate into the device’s internal pressure fluctuations, and then piston rod vibrations transmitted to the body of the vehicle. It has been identified the pressure fluctuations are due to the valves’ inadequate performance. The dynamic effect known as rattling is detrimental to the passenger’s comfort. The phenomena have unique noise/vibration characteristics which can be related to the valves’ operation within the frequency range usually from 200 to 600 Hz. In the paper the authors investigate the opportunities for identifying the transient phenomena characteristics using a time and frequency domain signal processing technique – Short Time Fourier Transform. They examine a number of damper configurations, test them, and then apply the technique for the purpose of analysing related symptoms. Finally, they draw conclusions.

1. Introduction

An automotive damper is a mature technology in the industry. From an engineering standpoint, the device design is a compromise between handling characteristics of a car, passenger comfort and safety, NVH and durability [1]. Recently, new automotive trends in vehicle chassis design have generated research and engineering efforts. The engine and powertrain vibration reduction, the entry of hybrid/electric vehicles have caused all vibration sources due to vehicle chassis operation recognizable by both driver and passengers [2]. Moreover, due to the increasing structural stiffness requirements imposed by vehicle OEMs (Original Vehicle Manufacturer) the energy dissipation efficiency of the damper has become a research and engineering challenge. It is, therefore, vital to propose means for eliminating or reducing their influence through changes that will result in vibration level reduction and techniques methods, metrics for evaluating them.
In the dampers any disturbances in the process of generating damping forces translate into the device’s internal pressure fluctuations, and then piston rod vibrations transmitted to the body of the vehicle. There is ample theoretical and experimental evidence that the pressure fluctuations are due to the inadequate performance of the valves in the vehicle damper [3]. The dynamic effect known as rattling or knocking noise is detrimental to the passenger’s comfort and is the source of audible noise in the passenger’s cabin of the vehicle [4-6]. The phenomena have unique noise/vibration characteristics which can be related to the valves’ operation within the frequency range usually from 200 to 600 Hz [7-10].

The selection of a proper method for analysing the transient phenomena occurring in the damper and a manner of their transfer to the body of the vehicle is an important step in the analytical process. The phenomena manifest their non-stationary characteristics as short, abrupt changes. Traditionally, Fast Fourier Transform (FFT) based techniques have been available for performing frequency-domain analyses, however, the time domain information (when using FFT based tools) is lost upon the transformation and they perform best when applied to stationary phenomena. To avoid the shortcomings of the conventional FFT tool several time-frequency distribution functions have been developed specifically for the purpose of analysing transient signals, namely, e.g. Short Time Fourier Transform (STFT), wavelet transforms, Wigner-Wille distribution functions and the like [11-14]. In general, the methods have been employed for analysing transient signals with changing frequency characteristics.

Briefly, there is a need for a systematic analytical procedure to handle the non-stationary events to aid in the vehicle damper development. As such, in the paper the authors investigate the opportunities for identifying the transient phenomena characteristics using a time and frequency domain based signal processing technique – Short Time Fourier Transform. They examine a number of damper configurations, test them, and then apply the technique for the purpose of identifying related symptoms. Finally, they draw conclusions.

2. Test setup
The test setup reflects the vehicle damper’s operating conditions in a real suspension of a passenger car. The test rig is illustrated in Fig. 1. As shown the damper’s outer tube (reservoir) is rigidly attached to the MTS actuator driving it according to the prescribed displacement input. The piston rod is attached to a flexible elastic top mount type fixture. The top mount’s housing is rigidly attached to the (upper) stationary MTS frame. The measurement system utilizes the LMS AD/DA data acquisition SCADAS III box for recording the data.

![Figure 1. Data acquisition system layout and test rig](image)

Rod acceleration $a_{PR}$ (and displacement $x_{PR}$), stroker’s displacement $x_e$, force $F_d$ are then recorded simultaneously using the accelerometer PBC 353B34, the MTS’s LVDT sensor and the MTS’s force sensor, respectively. Throughout the measurements the sampling frequency was equal to 15 kHz. The STFT spectrograms were calculated off-line on completing the measurements. It should be noted that
Figure 2. Rod acceleration time history: all configurations

although the test rig does not reproduce the exact operating conditions of the examined dampers on the car, it is sufficient for comparison purposes and delivers good quality data.

Throughout the experiment the authors examined the performance of a prototype take-apart twin-tube damper unit by subjecting it to a sinusoidal displacement input at the peak velocity of 0.188 m/s (peak displacement amplitude equal to 2 mm) and the frequency of 15 Hz as previously described. The piston rod diameter of the tested unit was 14 mm, and the inner cylinder inner diameter equal to 32 mm. The examined damper is a typical unit of twin-tube design with one set of deflected disc type valves.
located in the piston, and the other one in the base (foot) of the damper; the details of a twin-tube damper operation are omitted here as the knowledge is considered common.

The base 32/14 configuration was then successively modified by altering the valves in the damper by changing: 1) compression orifice size (piston valve), 2) compression disc stack thickness (piston valve), 3) compression orifice size (base valve), 4) rebound-side intake disc thickness (base valve). The modifications resulted in 5 (4+1 incl. the base design) different data sets and their measured static force-velocity characteristics are highlighted in Fig. 2a. In the presented graph the compression force is positive, and the rebound force is negative. The force-velocity characteristics are presented here merely for the purpose of part-to-part comparison. It should be noted that not all variants resulted in distinct static force-velocity characteristics (see e.g. rebound intake disc case in Fig. 2a). The modifications due to the orifice size had the biggest impact at velocities below 0.4 m/s, and altering the disc stack stiffness influenced the damping forces above appr. 0.2 m/s.

For each configuration the authors extracted the displacement $x_e$ and the acceleration $a_{PR}$ which were then post-processed off-line using MATLAB R2017b.

### 3. Results

In this section we reveal the experimental results followed by an analysis of the post-processed data using the Short-Time Fourier Transform (STFT) procedure.

#### 3.1. Short-Time Fourier Transform

By definition the Short Time Fourier Transform for a discrete time signal is obtained by computing the Discrete Time Fourier Transform (DTFT) on a signal broken into overlapping segments [15]. For each segment the DTFT is calculated and the complex result is recorded at each time and frequency. In the examined case the STFT output is calculated for the rod acceleration signal $a_{PR}(t)$. In this study the authors employed several window functions for examining the time-frequency characteristics of the acceleration signal, namely, rectangular window, Hamming window, Hanning window, exponential window, and an in-house window function (or the MS window function) revealed in Fig. 3.

![Figure 3. In-house MS window function](image)

With STFT the choice of a well-performing window function and its width is critical. It is well known that in time-domain narrow windows yield good time-domain resolutions but inferior ones in frequency domain and vice versa which leads to a compromise between time resolution and frequency resolution [15]. Next, the shape of a window function is equally important as the window is also the source of spectrum leakage and artificial artefacts in the calculated spectra.

Therefore, in this paper the authors propose a new window function (named MS window functions) that, in the authors’ opinion, is specifically tailored for capturing the transient characteristics of the acceleration signal in the experiment. The MS window function is a hybrid window that combines the characteristics of the rectangular window and the Hanning function as shown later in the outcome of the study.
3.2. **Analysis**
Here, the authors present the experimental results in Figs. from 4 to 8. As mentioned, Fig. 2 contains time histories of the measured piston rod acceleration signal $a_{PR}$ for the damper configurations revealed in Fig. 2a and described in the previous section. It can be seen the transients occur at the piston rod motion reversal points (i.e. rebound-to-compression and vice versa). In general, it should be noted, too, that the transients amplitude is different when switching from rebound to compression vs. compression to rebound. For each of the configurations the authors calculated spectrograms (revealed in Figs. 4 to 8) and presented the STFT snapshots at the frequency $f=400$ Hz (corresponding to the magnitude of the characteristic component in the FFT spectra).

![Spectrograms: base configuration](image)

**Figure 4.** Spectrograms: base configuration
The presented spectrograms were calculated using 20 ms window functions with a 95% overlap to yield a 1 ms resolution.

It should be noted that the rectangular window function provides a precise amplitude information but the spectrum leakage and artifacts can be clearly seen in the output data (see e.g. Fig. 4a, 5a) as light blue vertical stripes which makes the rectangular window based approach virtually unusable.

On observing the data in Figs. 4 to 8 it seems that of the remaining four window functions (Hanning, Hamming, exponential, MS) the performance of the Hanning and Hamming windows, respectively, is almost identical. The spectrum leakage is less with the two window functions, however, their ability to capture the amplitude/time information is inferior to the exponential and MS

![Figure 5. Spectrograms: base configuration modified by changing the orifice size (piston valve)](image-url)
window functions, respectively. Next, the advantage of the MS window over the exponential one can be seen, e.g. in Fig. 5f. The exponential window is efficient at capturing the time information but the amplitude error is significant. The MS window (which is a combination of the rectangular window and the Hanning window) seems to combine the advantages of the two window functions. Specifically, the leakage is reduced and the time-domain accuracy is improved. This was achieved with a relatively low information loss, i.e. less than 25% amplitude error and less than 18% energy error.

![Spectrograms: base configuration modified by changing the orifice size (base valve)](image-url)

**Figure 6.** Spectrograms: base configuration modified by changing the orifice size (base valve)
Figure 7. Spectrograms: base configuration modified by changing the disc stack stiffness (compression side stack in the piston valve)
Figure 8. Spectrograms: base configuration modified by changing the rebound side intake disc (base valve)

4. Summary and conclusions
The purpose of this study was to lay the foundations for a systematic analytical procedure for handling transient phenomena occurring in vehicle suspension dampers (and effectively transferred to the body of the car). To summarize, the authors examined the output of five configurations of a double-tube vehicle damper subjected to oscillatory medium frequency inputs in a test rig developed to approach its operating conditions on the vehicle. Not all of the examined valving configuration had an influence on
the damping force output yet they impacted the piston rod acceleration. The study also shows that the damper configuration can be effectively manipulated in order to optimize the vibratory characteristics of the damper-top mount unit (yet at the cost of primary/secondary ride characteristics). The output of this study also highlights the STFT procedure can be an efficient tool for capturing the transient phenomena. The presented MS window function is a well-performing hybrid approach to capture both the amplitude and the frequency content of the analysed signal. Finally, further steps will be directed towards expanding the procedure with wavelet transforms and the Wigner-Wille distribution.

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