

Systematic Brake Development Process and Optimized Robust Design of Front Axle Kinematics in Order to Reduce Oscillation Sensitivity

Albert Schlecht and Bernd Heissing
Technische Universitaet Muenchen

Jan Muenchhoff
Audi AG

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ABSTRACT

Brake judder is about oscillations excited by brake application, which are generated in the contact area between brake pad and brake disc and are transmitted by the elements of the suspension to body and steering system. The driver perceives these perturbations as brake pedal pulsations, steering wheel rotational and body vibrations. The evaluation of a suspension concerning brake judder often takes place for the first time in road tests, since established simulation processes with a high significance concerning ride comfort are missing. At such a late moment necessary modifications in the development process are only hardly possible and very expensive. For avoiding brake judder a systematic development process is needed for brake and suspension. Each one can separately be improved in measurably borders so that their assembly is free of cold brake judder. The present paper shows appropriate test and simulation methods to achieve this.

INTRODUCTION

Brake judder can be divided in two groups - cold and hot judder. C. Bittner [1] defines the area under 200° Celsius disc temperature as cold judder and above as hot judder. In both cases geometric defects of the brake disk cause brake torque variations (BTV) which result in steering wheel rotational vibrations, body vibrations and brake pedal pulsations and in the case of hot judder additional in noise. At cold judder the brake torque variations are especially in the 1st and 2nd order of the wheel turning frequency caused by DTV (Disc Thickness Variation)

due to cold disc wear. Higher orders can be measured at hot judder due to geometric modifications of the disc surface (Hot Spots) after thermal load. As it is difficult to enable reproducible test conditions for hot judder the focus of this paper is on cold judder. Numerous papers can be found in literature about the excitation (a selection: [4], [5], [6], [7], [8]) and the transmission (a selection: [1], [2], [3], [9], [10], [11], [12]) of brake moment and brake pressure oscillation up to the drivers perception [9].

The purpose of this paper is to show, that in the view of a automobile manufacturer the brake as judder source as well as the suspension as judder transmitter (concerning body and steering wheel rotational oscillations) can be analyzed separately in the product development process concerning their contribution to the brake judder sensitivity and can be optimized resulting in defined boundary values. The analysis of the brake can be done experimental or using simulations ([5], [7], [8]). The automakers mostly purchase brakes from their suppliers and so they do not have simulation models of brakes with a high quality. For this reason it is convenient to measure the level of the brake torque variation at a brake dynamometer or a test car. The suspension as a transmission path can be optimized in a good way in simulation and the necessary models are present at the most OEMs. For application of the simulation a valid simulation model and an evaluation method is needed, which represents the subjective judgment of the test driver. Additionally a graphical tool is needed, that shows measurement and simulation results in a comparable design to provide a fast comparison of both. Measured

road test data must include information about the excitation, the transmission path and the output signals of the system (steering wheel, body) for this comparison. Forces and torques at wheel are detected with 6 component measuring wheels. To get an overview about brake and suspension systems on market three middle class vehicles are tested in a brake judder benchmark with prepared brake discs at the front axle. At the rear axle standard discs are in use. The prepared discs have a maximum DTV of $20 \pm 2 \mu\text{m}$ (1. Order $> 15 \mu\text{m}$, 2. Order $< 6 \mu\text{m}$) and a Run-out of $30\text{--}50 \mu\text{m}$. The compared braking tests in the paper start at a speed of 160 km/h and decelerate constantly with $0.2g$, $0.3g$ and $0.4g$. The disc temperature before the braking is less than 100°C . To simplify matters in the following only brakings with $0.2g$ are represented, because from experience this braking represents the worst case in test and simulation.

OBJECTIVE EVALUATION METHOD FOR BRAKE JUDDER

For modeling the test driver judder evaluation the subjective opinions of test drivers are correlated with measured accelerations. As it is not clear, which input measuring point has the biggest influence to the human oscillation perception, different measuring points are recorded and analyzed with the correlation analysis (see Fig. 1).

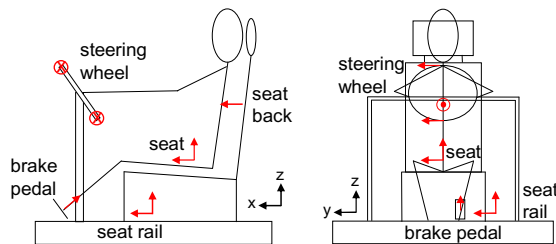


Fig. 1: Measuring points of the acceleration sensors

To create a spectrum of subjective opinions as huge as possible prepared discs with different DTVs (maximum DTV in the first order) are assembled to a test car. The tests are executed with different decelerations at an initial speed of 160 km/h . Four test drivers executed the tests with an upper class vehicle and the number of tests amounted to 160. The recorded acceleration signals are high-pass-filtered so that the static parts of the oscillations are cut off and filtered with the VDI-2057 frequency weighting filters [13]. These filters consider the human oscillation sensibility dependent on the frequency content of the oscillations. The frequency weightings will differ for the various vibration axes and measuring points. The WD filter is used for the whole-body oscillations, the WH filter for the steering wheel rotational vibrations and the WK filter for the brake pedal pulsations. As characteristic value of the braking the maximum value of the sliding rms in the regarded time window is extracted. The VDI-2057 weighting filter is

appropriate for the brake judder excitation, since almost only periodic oscillations are present, which do not exhibit impact portions. In Fig. 2 the correlation of the maximum values of the frequency-weighted sliding rms of the seat rail acceleration with the subjective judgment of the test drivers (use of a tenner scale; best mark=10) is plotted regarding the body oscillation. As the coefficient of correlation (R) is 0.97 this application exhibits a high validity. This correlation represents the best correlation regarding the body oscillation compared with other sensor signals (seat or seat back). The correlation function for the evaluation of the steering wheel rotational oscillations is generated by the difference of the upper and lower steering wheel sensors. With the difference of the signals the oscillation in y direction can be eliminated. With this approach R amounts to 0.95 . For the correlation of the brake pedal signal the acceleration sensor at the brake pedal is used ($R=0.92$).

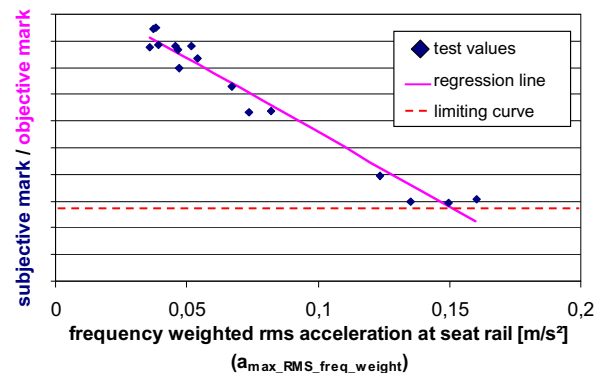


Fig. 2: Correlation of the subjective test driver marks with the VDI 2057 frequency weighted maximal rms-acceleration-values at seat rail.

With the regression line regarding steering wheel rotational, brake pedal and body oscillations the weighting functions can be set up to derive objective evaluations from measured and simulated data. The weighting function has the following form:

$$\text{objective_mark} = m \times a_{\text{max_RMS_freq_weight}} + t$$

The test driver evaluation is linear just up to an asymptote. Below this line the subjective marks do not decrease although the amplitude of the oscillation increases. This behavior is not integrated in the evaluation model. Thus objective marks with a negative value are possible. Although it is statistically not correct to extrapolate the model out of the valid value area for researches using the simulation relative changes are interesting. For the interpretation of negative marks it means that this perceived oscillations a test driver would evaluate with a mark near the limiting curve.

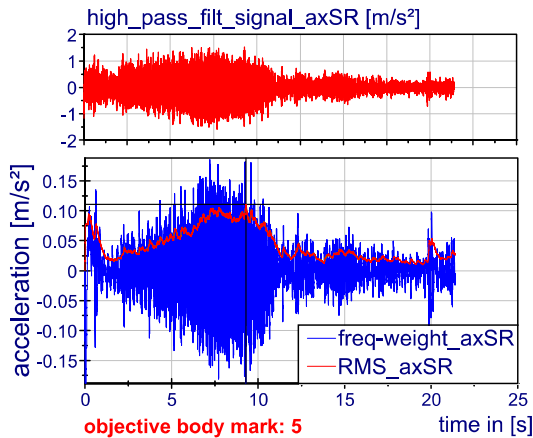


Fig. 3: Plot of the automated signal analysis for the brake judder evaluation

Fig. 3 shows an exemplary result plot for an automated evaluation for driving and simulation tests. The upper diagram represents the high-pass-filtered acceleration signal. The lower plot shows the frequency weighted acceleration, their sliding rms and the objective body mark.

ANALYSIS METHOD

For the holistic analysis of the phenomenon brake judder a representation is needed, which contains excitation, transmission and output signals. As cold judder concerns an excitation in the 1st order of the wheel rotary frequency (use of prepared disks with a sine of 1st order over one rotation), an order analysis can be used. The order analysis of the seat rail acceleration is exemplarily shown in Fig. 4. To fade out the static portions and to eliminate sensor drift the analyzed signals are high-pass-filtered at first (e.g. see upper plot in Fig. 3). The signals are converted to decibel. The oscillation amplitudes (various colors, z-axis) are plotted against the orders (x-axis) and the wheel rotary frequency (y-axis).

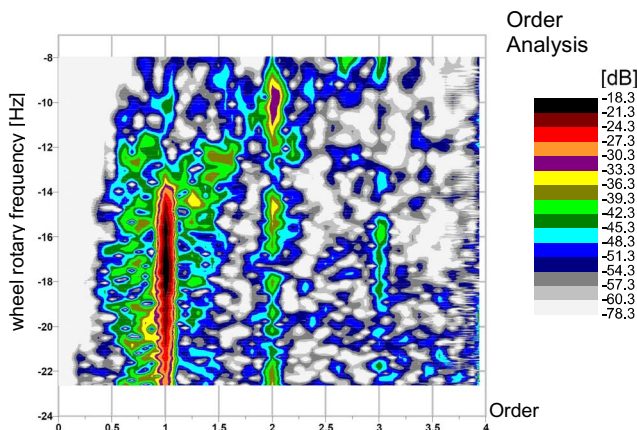


Fig. 4: Order analysis of the seat rail acceleration

To show the time flow of the braking, the scale of the y-axis is chosen from negative to positive (bottom-up) values. The braking starts at the bottom and ends on the top of the plot.

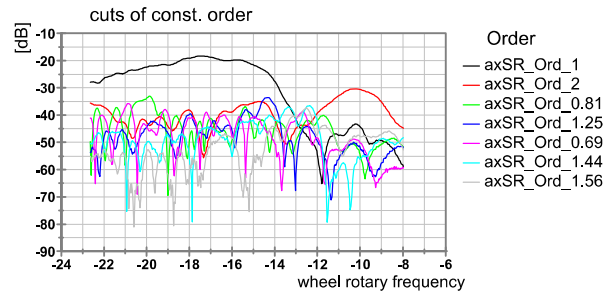


Fig. 5: Cuts of constant order out of the order analysis in Fig. 4

From the order analysis the 7 maximum cuts of constant order (vertical cuts in Fig. 4) are extracted (see Fig. 5). The envelope of these cuts of constant order is transferred into the overview information sheet of the order analyses (see green line in Fig. 6) and plotted there with the further envelopes.

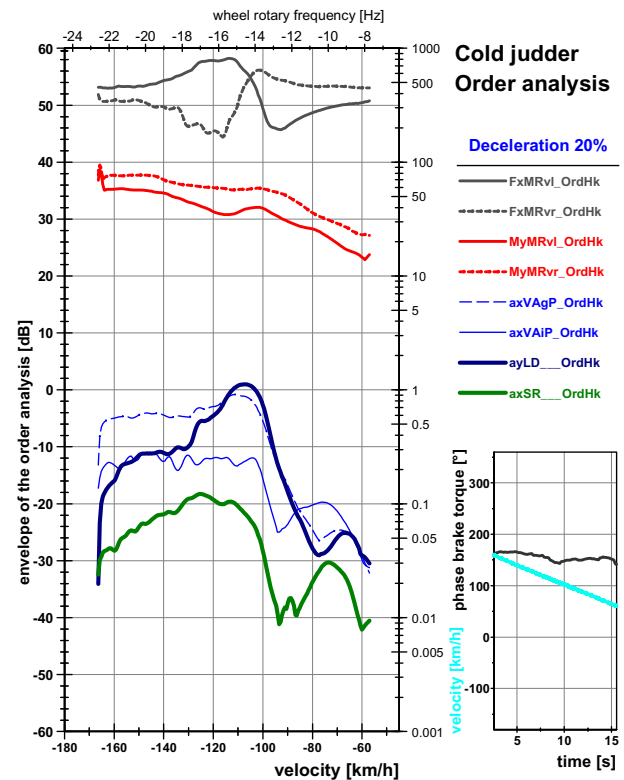


Fig. 6: Summary of the order analysis for a cold judder brake

All units are standardized on dB and so it is possible to represent values from 1000N up to 0.001 g in one plot. For a better interpretation of the curves the linear equivalent values are shown. To show the time flow of