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Startup and Bifurcation Behavior of Non-Linear Stick-Slip Vibrations: Creep Groan Occurrence for Increasing and Decreasing Speeds

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ABSTRACT: Creep groan is known as an important cause of warranty issues related to disk brake systems. Creep groan's self-excited and stick-slip related mechanisms lead to strongly perceptible noise and vibrations. Due to creep groan's non-linear nature, resulting limit cycle vibrations are known to depend on the operating parameters present in experiment or simulation.

So far, this dependency on parameters such as brake pressure and vehicle speed has only been investigated for strongly reduced systems. These reduced systems were often not able to cover all bifurcation phenomena found within vehicle tests. Vehicle tests are, however, more difficult to control, which complicates the detection of stability regions on the full system. In addition, little attention was paid to the startup of creep groan vibrations until now, as most studies focused on the analysis of fully developed creep groan signatures.

This study tries to cover this knowledge gap; to discover and explain bifurcation behavior as well as the startup of creep groan vibrations. The investigated system was chosen big enough to show the main bifurcation effects but small enough to be easily controlled: Half-axle tests were performed on a drum-driven test bench. During the tests, creep groan limit cycles were approached for different brake pressures by increasing as well as decreasing speeds.

The results give detailed insight in the highly-transient mechanisms of creep groan startup. Two different bifurcations, low-frequency creep groan at approx. 21 Hz and high-frequency creep groan at approx. 75 Hz, were found. A certain 'transition' groan was found as a phenomenon between both stable groan regions. The direction of approach – increasing or decreasing speed – clearly led to different stability regions. Based on these findings, recommendations for future investigations can be derived: Simulative and experimental models should be able to perform both low- and high-frequency groan. Both increasing and decreasing speeds need to be considered in creep groan analysis as well. This can be crucial for the design of simulation models and test procedures in future.

KEY WORDS: Bifurcations, Creep Groan, Half-Axle Test, Non-Linear Vibrations, NVH, Stick-Slip

1. Introduction

1.1 Motivation

Creep groan is known as a non-linear, stick-slip related NVH problem of disk brake systems, [1]. Especially within the Asian passenger vehicle market, creep groan and other phenomena lead to numerous warranty cases – resulting in a reduced quality perception and approx. $100 million brake NVH warranty costs per year, as SAE [2] estimates. Developments towards electrified drivetrains in combination with more and more stop-and-go traffic and automated driving functions further favor groan occurrence, [3]. To tackle this rising problem, detailed knowledge about the phenomena's mechanisms is necessary. This work tries to further enlighten the aspect about creep groan startup and bifurcation behavior.

1.2 Creep Groan: State of the Art and Mechanism

Creep groan is loosely defined as a self-excited, low-frequency vibration with dominant frequencies in a more or less defined range of 20-200 Hz, [4]. Creep groan vibrations are further characterized by stick-slip sequences between the brake disk and pads, [1, 5, 6]. These repeated stick-slip sequences occur when low vehicle speeds are combined with a sufficiently high enough brake pressure, [7]. During creep groan action, these stick-slip sequences mark a change from pretension phase to a damped oscillation phase with sliding friction, as explained by the analogy to playing a violin within [8]. Recent results within [9] suggest the additional occurrence of vibro-impact effects during certain stages of creep groan, when normal contact between disk and pads is lost.

The non-linear nature of stick-slip and vibro-impact related creep groan certainly leads to an interesting bifurcation behavior. The authors' studies [7, 10, 11] have already shown the occurrence of two different creep groan phenomena for two different half-axle setups. Both a 'low-frequency' groan at approx. 15-25 Hz as well as a 'high-frequency' groan between 60-100 Hz were found in experiments as well as simulations. During these experiments, measurements were taken after decreasing the drum speed towards a given value. Hence, three stability regions were found: no groan, low-frequency groan and high-frequency groan.

A different approach is shown by Zhao et al. within [12]: Here, a linearized stability analysis was performed on a two-mass minimal model of an idealized brake, utilizing the bristle friction law. The resulting stability map contained again three different regions. In contrast to the authors' studies, these were: definitely no stick-slip, no stick-slip or stick-slip (two stable solutions, depending on the way each operational point was reached) or definitely stick-slip. This behavior was also confirmed in experimental tests of the corresponding minimal model and a half-axle model without tire. By increasing or decreasing the drive shaft speed, the bifurcation borders between the three regions were found in well correspondence to numerical stability results in [12] and to analytical investigations in [13]. However, only one creep groan manifestation was shown and documented, probably relating to the reduced setup without a wheel and the excitation via a drive shaft.

Meng et al. [3, 9] show another approach based on vehicle tests and a multi-body simulation of the brake system. Here, brake pressure was varied while the vehicle was initially standing on a hill. In the shown time-frequency spectrograms, different creep groan phenomena can be found: Again, low-frequency as well as high-frequency groan can be seen, accompanied by certain 'transition' phenomena in between. Groan phenomena are distinguished differently within these works; especially half-order components are treated with emphasis. It should be noted, that the occurrence of these components in frequency spectrum is related to what will be called 'transition' groan as well as low-frequency groan within the present paper.

Dynamic groan, a term found within brake NVH literature, should be differentiated from this work's focus on creep groan reached by a decreasing speed. Dynamic groan is described as a low-frequency, order based noise with its pitch directly depending on vehicle speed, [14]. This speed-dependent behavior suggests an excitation mechanism different to that of creep groan but more similar to brake judder / DTV. Within [15] however, dynamic groan is defined by its relation to a 'negative damping' friction-velocity characteristic, which can also be found in a creep groan context.

1.3 Scientific Approach

Several creep groan phenomena were found each within vehicle or half-axle tests from literature. The way the measurement points were reached, i.e. by increasing or decreasing speed, was not clear or only unidirectional in these cases.

Fundamental works on (even more) reduced systems however have shown a distinct dependency of the resulting creep groan manifestation towards these initial speed or pressure conditions while at the same time, only one creep groan manifestation was found.

Within this present research paper, a combination of both approaches is taken. Experimental tests on relatively detailed half-axle level are performed for increasing as well as decreasing speed at constant brake pressure. The results regarding bifurcation behavior and creep groan startup further complete our picture about complex creep groan phenomena.

2. Methodology

2.1. Test Setup

Figure 1 shows the test bench setup at the combined suspension and brake test rig. Here, the front axle of a compact executive car is mounted on the air-sprung test bench frame by a (yellow) subframe. Only one half-axle is investigated; the left front wheel is driven by the drum. Pre-loading according to the vehicle's weight is adjusted by vertically moving the drum platform.

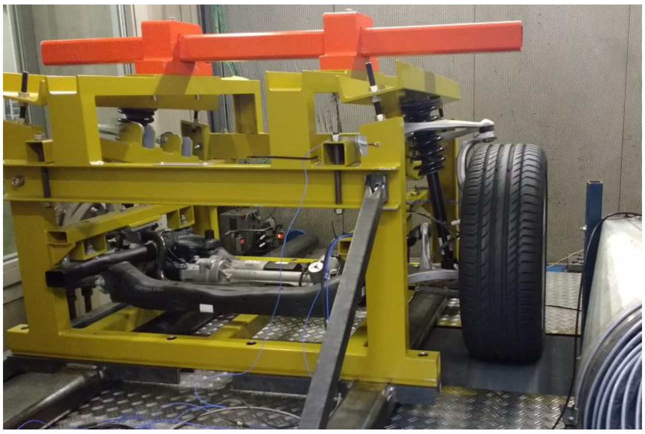

Figure 1 Half-axle test bench setup for creep groan investigations at FTG/TU Graz

The investigated series axle is a double wishbone setup with two separated lower control arms. Brake torque is provided by a floating caliper brake with a ventilated gray iron disk; ECE brake pads are used. Drive torque is introduced by the drum (Ø1.2 m), which is rotated by a 375 kW peak external rotor electric machine. Further parts of the setup include the deactivated and fixed steering gear, the stabilizer bar with links as well as the integral subframe.

Despite a more sophisticated sensor setup mounted for test monitoring and control, only the sensors according to Table 1 are relevant for this study. Mounting positions of both accelerometer as well as rotary encoder are shown in Figure 2.

Table 1 Relevant sensor setup

Sensor	Position	Type
triaxial accelerometer	top of caliper anchor bracket	PCB 356A02 (piezoelectric)
rotary encoder	side plane of drum near outside Ø	Scancon SCA24 – 7500 (incremental)

Creep groan occurrence and stick-slip frequencies are evaluated by the (local) z-acceleration of the accelerometer on the caliper anchor bracket. A fine resolution of the drum/vehicle speed is calculated from rotary encoder data by assuming slip-free rolling on the drum's side plane.

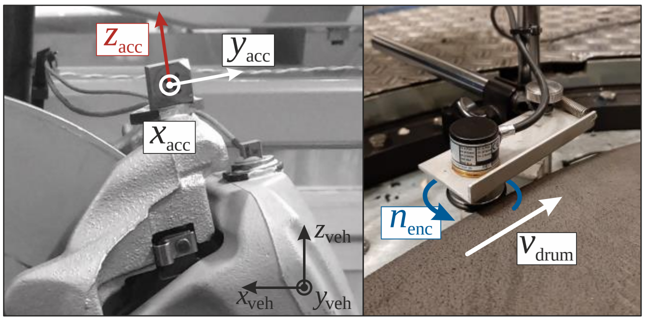

Figure 2 Relevant sensors: caliper anchor bracket acceleration and drum/vehicle speed

2.2. Test Procedure

First, a bedding procedure similar to SAE J2521 was performed, [16]. As no direct torque measurement was installed, bedding brakings from 80 to 30 km/h were performed by assuming constant deceleration rates calculated from simple longitudinal dynamics. Therefore, a mean coefficient of friction μ = 0.42 was assumed, which was in well correspondence with already existing performance data of the used friction parts. Overall, bedding consisted of 318 brake events with different brake pressures between 15 and 51 bar. Test bench airstream was set to 80 km/h and 20°C, differing from [16].

Before each test sequence, intermediate conditioning similar to SAE J2521 was applied; following the same restrictions regarding torque control as the bedding sequence. Therefore, 24 conditioning brakings from 50 to 30 km/h at different brake pressures were conducted; with cool down phases to 100 / 150°C respectively. Test bench airstream was set to 35 km/h and 20°C. [16]

Figure 3 shows the load profiles of the test sequence itself. During each test, brake pressure is held constant at either 10 or 20 bar while the speed is gradually increased or decreased with gradients of 0.01 (km/h)/s in the most relevant range between 0 and 0.6 km/h drum/vehicle speed. Between 0.6 and 1.5 km/h, the speed gradient was set to 0.045 (km/h)/s.

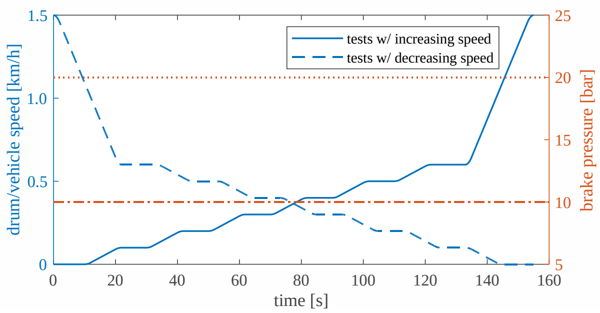

Figure 3 Load profile for creep groan tests

Environmental conditions within the climate chamber of the test bench were set to 20°C and 50% RH.

3. Results and Discussion

The evaluation of test results is performed in a two-fold manner.

First, each test run result is split into time intervals of 1 s. Each interval is then checked for creep groan occurrence and its dominant groan frequency by a method adopted from [7]. Therefore, the caliper anchor bracket z-acceleration signal is offset-corrected, brought to frequency domain and filtered. This preprocessed signal then undergoes a peak detection for values above a threshold of 0.1 dB re 1 m/s^2, chosen by experience. A check for super-harmonics leads to a decision regarding occurrence and dominant groan frequency, which is then displayed in a bifurcation plot of vehicle speed over brake pressure.

Second, time sequences containing characteristic creep groan startup are analyzed. Again, the z-acceleration of the caliper anchor bracket is under investigation. Time series as well as frequency plots are shown. Further insight is given by time data of the drum/vehicle speed estimate based on the rotary encoder.

Both results are then compared to experimental and simulative data within literature.

3.1 Bifurcation Behavior

Figure 4 shows the measured bifurcation behavior of the axle. On the left hand side, groan occurrences during tests with increasing speed are shown. On the right hand side, tests with the decreasing speed profile are treated. In any case, the occurrence of creep groan within each 1 s time sequence is marked by a colored square. Colors relate to the dominant groan frequency as indicated by the colorbar in the middle.

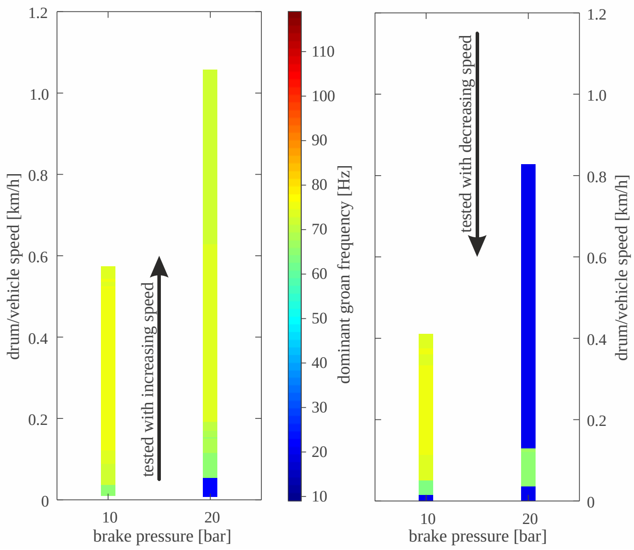

Figure 4 Tested creep groan behavior for increasing and decreasing speeds at p_B = 10 / 20 bar

For increasing speeds, mostly high-frequency creep groan between 73 and 76 Hz can be found in Figure 4, left. Higher brake pressure enables groan vibrations at higher speeds; the creep groan zone at 20 bar is almost twice the size of the creep groan zone at 10 bar brake pressure. Until the end of groan occurrence at rather high speeds, dominant groan frequencies are slightly decreasing; with the sound becoming more and more tonal. At very low speeds, the 20 bar test showed characteristic low-frequency groan with a dominant 1st order frequency of about 21-22 Hz, followed by a 'transition' groan with similar 1st order frequencies but dominant

3rd order frequencies at approx. 68 Hz. This 'transition' phenomenon can also be found directly after creep groan startup for the 10 bar test.

For decreasing speeds, Figure 4 on the right draws a significantly different picture: Whereas the 10 bar test is still very similar to the increasing test, the 20 bar decreasing test leads to low-frequency groan at 21-22 Hz for highest speeds at approx. 0.82 km/h. Interestingly, both decreasing tests show a 'transition' zone with a dominant 3rd order frequency of 68 Hz for low speeds. Before the final stop, again a 21 Hz creep groan occurs for a short duration.

Overall, three different creep groan manifestations can be observed: low-frequency groan at approx. 21 Hz, high-frequency groan at approx. 75 Hz and a 'transition' groan with a dominant 3rd order frequency of 68 Hz. Depending on the tested load profile, areas of creep groan manifestations switch at different points. This is especially clear for the end/beginning of groan at high vehicle speeds. Furthermore, all tests showed low-frequency or at least 'transition' groan behavior near zero speed.

3.2 Creep Groan Startup

Within the following figures, creep groan startup is treated in time and frequency domain. Therefore, the measured caliper anchor bracket z-acceleration is shown in a 10 s window within each first subfigure. A detail of the middle 1 s is shown in the second subfigure. The third subfigure contains the RMS amplitude in frequency domain for the 1 s window indicated by the orange, dotted lines in each top subfigure. As an additional information about drum/vehicle speed, results from the rotary encoder on the drum outside diameter are given in the fourth and last subfigure.

Figure 5 shows creep groan startup at 10 bar brake pressure and (almost) zero speed. As one can see in the top, creep groan actually already starts at approx. 2.8 s. Here, the 'transition' groan occurs, with two or three stick-slip sequences shortly after each other followed by damped oscillations of irregular duration. These individual stick-slip sequences can be identified by their sharp negative acceleration peaks, caused by the change from global stick to global slip. Certainly, these acceleration peaks excite a broad spectrum of natural frequencies. At 5 s, a qualitative change from the 'transition' groan towards a high-frequency creep groan at 73 Hz can be observed, see the second subfigure. This change is also connected with an increase of the drum/vehicle speed from approx. 0.02 to 0.045 km/h.

Figure 6 shows again creep groan startup from standstill but for 20 bar brake pressure. Here, a very clear low-frequency creep groan action with distinct stick-slip events repeated with 21 Hz occurs. Interestingly, the lowest subplot indicates already some positive drum/vehicle speed before the first slip occurrence. This could be related to the pretension phase; with the shape of the curve being influenced by the test bench drum speed control. Again, virtually no vibration is observable before the first stick-slip sequence. See once more some stick-slip cycles containing two repeated stick-slip sequences each in the second subfigure.

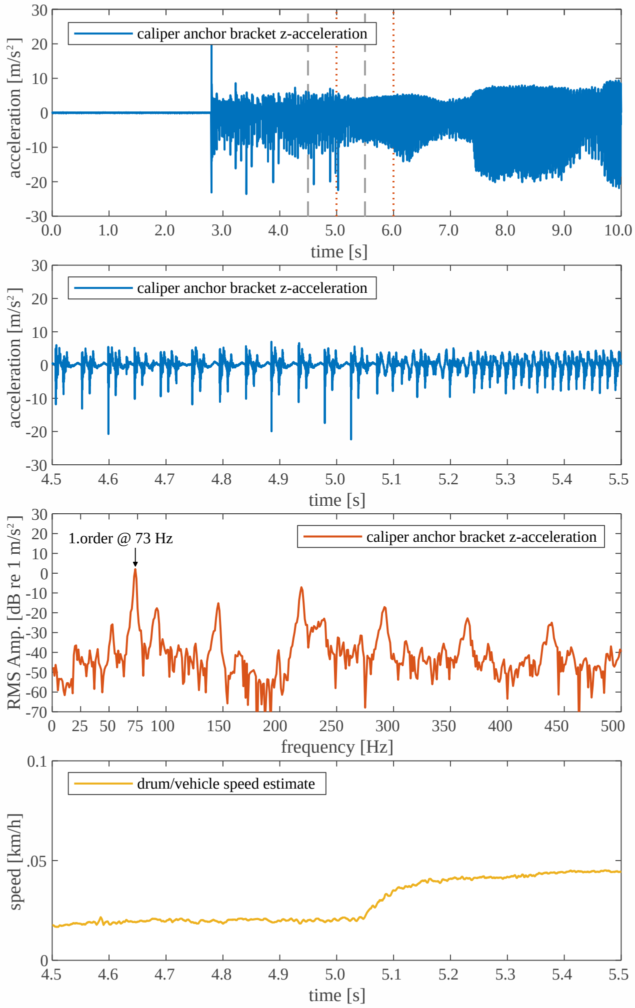

Figure 5 High-frequency groan startup for increasing speed at p_B = 10 bar: measured acceleration and veh. speed

Figure 7 shows creep groan startup during decreasing speed at approx. 0.38 km/h drum/vehicle speed. As one can see in the first subplot, oscillations are already present between 0 s and 4 s. These oscillations in the signals were found to be of rather harmonic nature at a frequency slightly below 75 Hz, most probably relating to movements of the upper control arm as described within [11]. At 5 s, the first stick-slip sequences can be found in the second subfigure, detectable by their sharp negative peaks. Within the frequency spectrum in the third subfigure, one can see the beginning phase of high-frequency groan – the first peak at 75 Hz is already clearly visible. A shift of the FFT time-window to a slightly later point in time would show further increased super-harmonic contents. Interestingly, there is also a significant peak at 21 Hz. The drum/vehicle speed signal in the lowest subfigure contains this 21 Hz oscillation too, indicating a harmonic movement of the whole axle system.

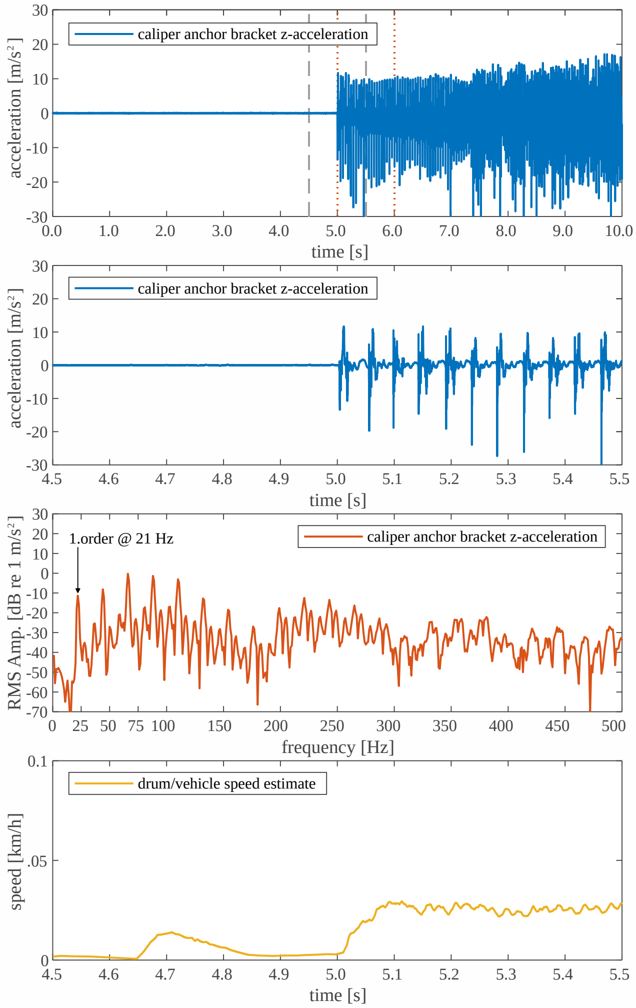

Figure 6 Low-frequency groan startup for increasing speed at p_B = 20 bar: measured acceleration and veh. speed

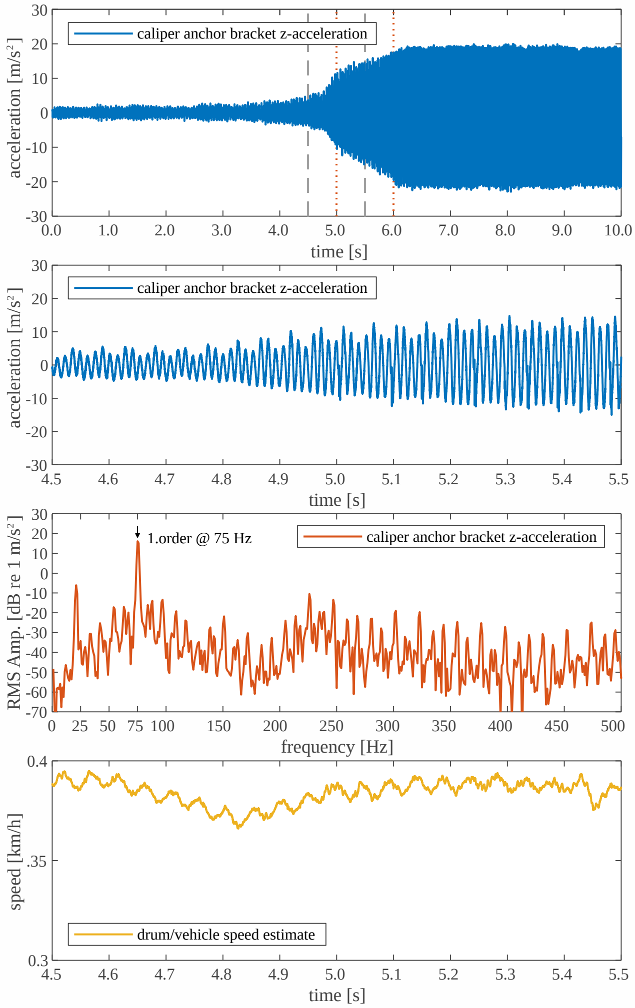

Figure 7 High-frequency groan startup for decreasing speed at p_B = 10 bar: measured acceleration and veh. speed

Figure 8 finally shows the creep groan startup for decreasing speed at 20 bar brake pressure. Again, oscillation content is already observable before the actual creep groan action. However, the increasing amplitudes result here in a 21 Hz low-frequency creep groan action, see second and third subfigure. Strong variations in drum/vehicle speed can be seen right before the beginning of creep groan, especially between 4.5-4.9 s. Nevertheless, a comparison with recorded signals of the internal test bench speed control indicate that these peaks could be spurious, probably related to particles or dirt on the running surface of the drum.

5. Conclusion

Similar to tests within [12, 13], clearly different instability regions were identified between tests with increasing drum/vehicle speed and tests with decreasing drum/vehicle speed. Creep groan vibrations occurred up to higher speeds at the increasing speed tests than at the decreasing speed tests. This non-linear behavior needs to be considered when comparing different test results of the same system; both in experiment and in simulation.

By choosing system boundaries wide enough and introducing the excitation force correctly at the wheel contact patch, two different creep groan phenomena were found: approx. 21 Hz low-frequency creep groan vs. approx. 75 Hz high-frequency creep groan. ‘Transition’ groan, similar to half-order content complex groan within full vehicle tests of [9], was found at rather low speeds between the low- and the high-frequency stability regions. Cycles of irregular length with two or three stick-slip sequences were found characteristic for this ‘transition’ groan.

An analysis of creep groan startup has shown that starting from zero speed typically results in low-frequency or ‘transition’ groan at first, with a switch to a large, dominating high-frequency groan range after a few seconds. However, low-frequency groan was found dominant at the higher brake pressure during deceleration from higher speeds. Similar results can be seen within [7], where decreasing speed was applied too. This behavior could explain the negligence of low-frequency groan within many works, as tests and simulations mostly focus on groan with increasing speeds from standstill.

Furthermore, quasi-harmonic oscillations were found right before the actual creep groan started during tests with decreasing speed.

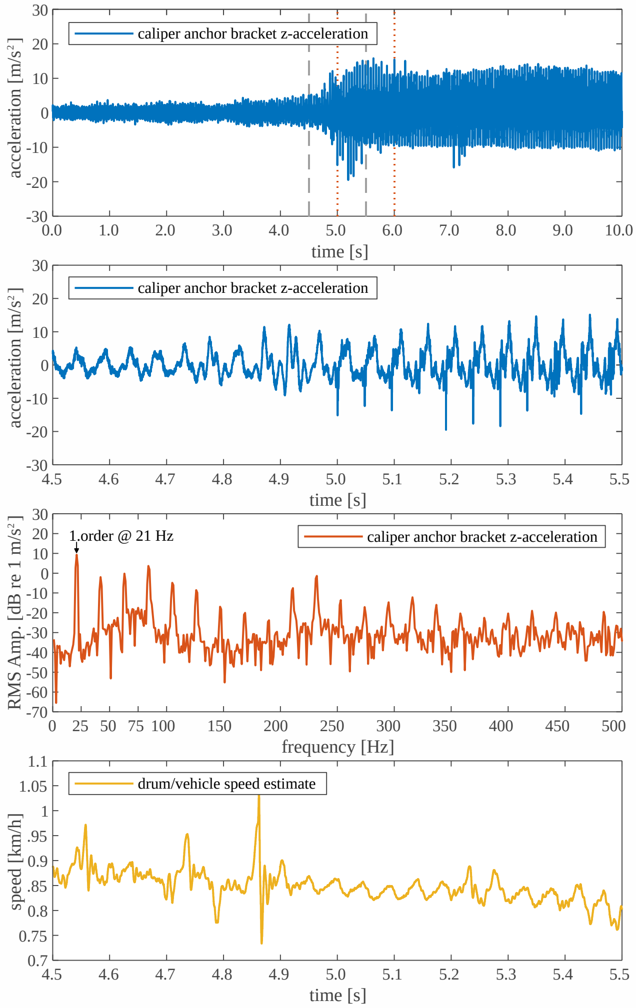

Figure 8 Low-frequency groan startup for decreasing speed at p_B = 20 bar: measured acceleration and veh. speed

These harmonic oscillations most probably relate to linear displacements of the axle and brake setup with frequencies near the later found dominant creep groan frequencies. Before the beginning of stick-slip action, an exponential increase of these harmonic amplitudes can be seen. Most probably, the relating (quasi-linear) vibration modes interact with stick-slip action during the fully developed, non-linear creep groan phenomena.

By analyzing the bifurcation behavior and underlying effects at groan startup, this work takes one step further towards a holistic understanding of creep groan phenomena. Based on the presented findings, the necessary extent of simulative and experimental models can be defined more precisely: Any reduced model should be able to perform both low- and high-frequency groan. In addition, test procedures should comprise of separate investigations for increasing and decreasing vehicle speed or at least consider the difference.

As an outlook, further effort should be put into finding explanations for the observed behavior. Especially the phenomenon of 'transition' groan could be observed in detail, by experimental tests as well as by numerical/analytical investigations.

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