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Friction Modes in Low Frequency disc-brake noise - experimental results and implications on modelling

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Today, low frequency disc-brake noises are commonly explained as self-sustained stick-slip oscillations. Although, at a first glance this explanation seems reasonable, there are indications that cast doubt on it. Indeed, experimental studies on groaning noises reveal two qualitatively totally different vibration patterns: stick-slip vibrations at almost vanishing relative speeds and another vibration pattern at low to moderate relative speeds. Within this article, experimental results are presented and discussed. Based on this, suggestions for appropriate mechanical models are derived.

1 Experimental setup and sensor placement

To investigate groaning noises of disc-brakes, experimental tests have been carried out at the laboratory of the institute. The test rig comprises a floating caliper disc-brake mounted on a front axle (both from series manufacturing). In the original setup, the brake pads – which are supposed to be mainly involved in generation of the considered vibrations – are totally hidden under the floating caliper (Fig. 1 a)). It is easily found, that the caliper – which is laterally attached to the support only by very soft elastic elements – does not contribute noteworthy to the force balance in the longitudinal direction (i.e. circumferential with respect to the disc). In fact, the pads are entirely supported by noselike extensions, while the caliper does only effect the normal force on the pads (Fig. 1 b)).

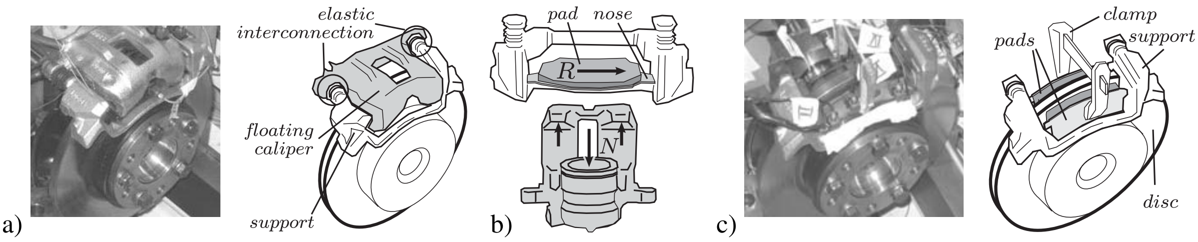

Fig. 1 a) Entire floating caliper disc-brake assembly. b) Functional schematic of the parts of the brake. c) Reduced experimental setup: caliper replaced by a screw clamp.

Therefore, to allow for a clearer view, the caliper has been removed and substituted by a screw clamp – providing the same functionality but giving direct access to the pads (Fig. 1 c)). A comparison of the results before and after the replacement showed a spectrum slightly shifted to higher frequencies (due to the reduced mass) while the groan phenomenon kept almost unchanged. Having the pads easily accessible, piezo acceleration sensors were put on one of them as well as onto the supporting structure. In addition to the acceleration sensors the measured pad was equipped with a little laser target to allow for measurements with a laser vibrometer (Fig. 2). The following results refer to the laser vibrometer data of the measured pad.

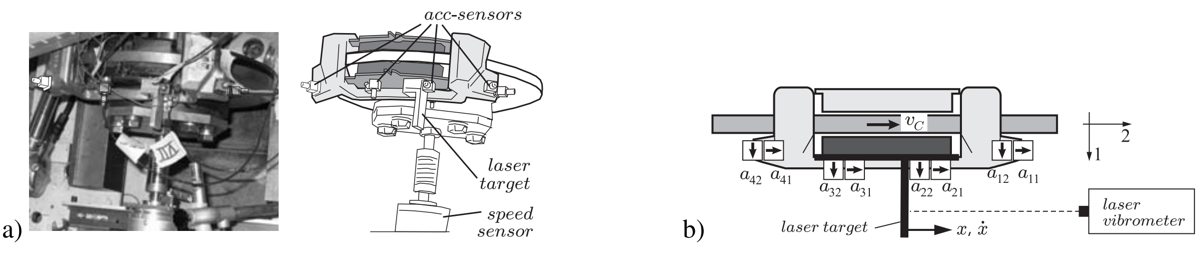

Fig. 2 a) Sensor placement (clamp and corresponding force-sensor missing). b) Sensor positions and orientations.

In operation, the driving motor is certainly not able to maintain the desired nominal speed n_N exactly. Therefore, in order to determine the actual speed v_C of the contact point as exact as possible, a rotational speed sensor as been attached directly to the disc, giving the actual revolution speed n_{act}.

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2 Longitudinal vibrations of the brake pads

Measurements indicate, that while groaning the pad's vibration is dominated by longitudinal motion, i.e. the 2-direction in fig. 2b). Figure 3 displays the state-variables $(x, \dot{x})$ of the considered pad for different (nominal) driving speeds. To allow for further interpretations, for each position x the according speed v_C of the contact point on the disc is also added to the plot. Strikingly, the pad exhibits two different motion types - although the acoustical impression appears almost the same and is

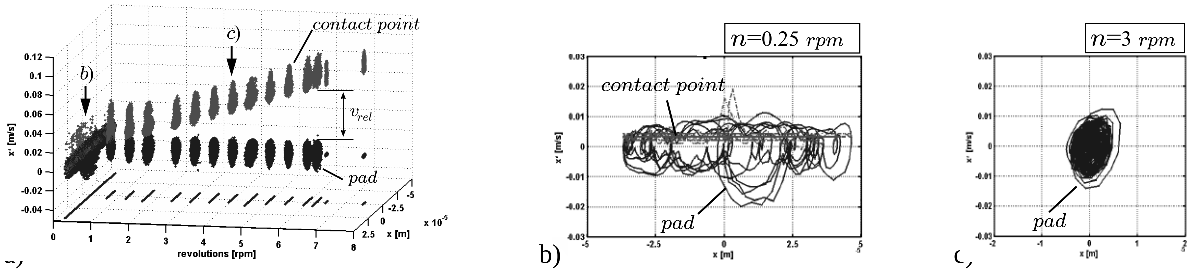

Fig. 3 a) State variables $(x, \dot{x})$ of the pad (black) and the corresponding speed of the contact point (x, v_C) (grey), plotted over the nominal revolution speed [min^{-1}]. b) Nominal speed of 0.25 min^{-1}: phase diagram $(x, \dot{x})$ (black) and contact point speed (x, v_C) (grey). c) Nominal speed of 4 min^{-1}: phase diagram $(x, \dot{x})$ (black), (x, v_C) out of display range.

dominated by contents at about 300 Hz, which refers to the lowest eigenfrequency of the disc. At very small driving speeds, the pad undergoes large vibrations (cf. fig.3 b)). The fact that the relative speed $v_{rel} = \dot{x} - v_C$ between pad and disc vanishes in some parts of the pad's motion suggests periods of stiction. For higher speeds, apart from minor oscillations, the contact point speed v_C scales linearly with the nominal driving speed. In contrast, the pad exhibits motions of a smaller amplitude and different pattern than before (compare fig. 3 b) to c)). Different from the contact point speed v_C, the pad's speed $\dot{x}$ does not scale with the driving speed – instead, its maximum stays constant over a wide speed range. Hence, the relative velocity v_{rel} increases with increasing driving speed, rendering the assumption of stiction periods implausible. The groaning sound emission and the pad's vibrations can be observed up to speeds of about 6.5 min^{-1}.

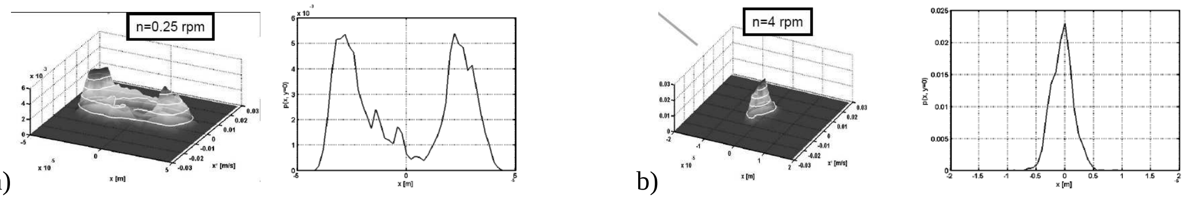

Fig. 4 a) Nominal speed of 0.25 min^{-1}: distribution density of $(x, \dot{x})$ (left) and Poincaré-section at $\dot{x} = 0$ (right). b) Nominal speed of 4 min^{-1}: distribution density of $(x, \dot{x})$ (left) and Poincaré-section at $\dot{x} = 0$ (right).

Looking at fig. 3 c), the question arises whether this behavior is periodic, probably hidden by noise, or not. Figure 4 shows 3-d distribution densities of the measured data $(x, \dot{x})$. Additionally, in the sense of Poincaré, sections of the distributions at $\dot{x} = 0$ are displayed. While for low speeds (0.25 min^{-1}, fig. 4 a)) a clearly periodic behavior can be observed, this is not the case for higher speeds (e.g. 4 min^{-1}, fig. 4 b)).

3 Conclusions

With appropriate parameters, former investigations on stick-slip vibrations show very good qualitative correspondence to the vibrations at low speeds [1]. Since stick-slip motion is not plausible at higher speeds, other explanations have to be found there. One possibility is a self-excitated friction oscillator with noisy decaying friction characteristic, causing and ceasing self-excitation. Investigations of a deterministic nonlinear oscillator with parameters according to measurements, show good correspondence to the observed ending point of the vibrations. Albeit, the model does not explain why the real system does not reach the stick-slip limit-cycle [2]. Another possible explanation is, that the displayed variables only span a sub-space of the state-space, which has a dimension too small to contain the periodicity. In order to construct appropriate models, it will be tried to reconstruct the state-space using additional measurement data or by means of time-delay embedding methods.

References

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[2] H. Hetzler, D. Schwarzer W. Seemann: Analytical investigation of Hopf Bifurcations occuring in a 1DOF sliding-friction oscillator with application to disc-brake vibrations, *Proceedings of ASME IDETC 2005, Long Beach, USA,* DETC2005-84312