

New Approaches to Signal Analysis of Friction Noise and Vibration

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1. Introduction

Up to now, there are no universal theories or friction models that cover all of the general phenomena of friction induced vibrations. The reasons for this are manifold: based on the complex friction process forces are transmitted, mechanical energy is transformed, surface topography is changed, interface material and wear may be removed and even physical and / or chemical properties may change. The operational conditions, the properties of the surfaces and the interfaces, their interaction, the environmental conditions and the time history lead to a friction coefficient - that is not an intrinsic property of participating materials alone. The identification of nearly all the above described properties is complicated by the problem of the inaccessibility of the contact area, which means that obtaining the characteristics of the friction interface is nearly impossible without significantly changing itself at the same time.

Friction induced vibrations may appear whenever two objects are placed in contact and are allowed to slide. Examples are found in the field of large scale objects as for instance earthquake excitation by friction in plate tectonics, narrow-banded noises when railway vehicles run through tight curves, friction in bearings, down to friction in micro scales in molecular physics.

Friction induced noise and vibrations of brakes, as one of the numerous technical applications in which these phenomena appear is still a field in which research efforts have to be made.

Brake systems are usually investigated with respect to linear stability of the steady sliding state. Although recent research in this field has been able to yield substantial progress, the limitation of most approaches lies in the restricted representation of the high dimensional phenomena of the friction interface and the multiple scales the mechanics are integrated in. Additionally, the - often even unknown - 'hidden parameters' mentioned above are neglected or not considered in most approaches.

Although the critical uncomfortable frequencies of brake squeal are certainly limited to the audible range and in case of structure-borne vibrations additionally to the infrasonic range, the tribological and structural mechanisms of the contact lead to broad-banded acoustic emissions at much higher frequencies. The sample rate of the conducted measurements was therefore increased to allow spectral components even in the ultrasonic range to possibly also reveal particle respectively wear patch dynamics sized in micro-scales [1, 2].

Following the considerations above the present study addresses the topic of brake squeal and vibrations from a different perspective. Instead of analysing a given numerical model for instability or limit cycles, experimental data of a brake system in non-squealing conditions is subjected to an experimental data analysis. Techniques of spectral analyses as well as of non-linear time-series analyses in different time-scales are applied.

The objective of the study is to identify presently still poorly understood parametric relationships of the dynamical system underlying the appearance of brake squeal, and to devise methods to do so. It is expected that the corresponding results will then later on be applied in the design of improved braking systems.

The paper is set up as follows: chapter two contains the description of the experimental approach enclosing the set-up and first results of a signal analysis in frequency domain. Subsequently primary time series analysis techniques are discussed and results of recurrence plots are presented. The implementation of phase space reconstruction methods and the application to the signal data is the content of the next chapter. Finally, the summary of the obtained findings and an outlook complete the present study.

2. Experimental Approach

In addition to vehicle testing, the assessment of brake squeal and vibration in automotive brake industries usually is investigated on noise dynamometers. To be as close to the mechanical environment of the vehicle chassis as possible, the complete brake system and even the entire vehicle corner are mounted and analysed (Fig. 1).

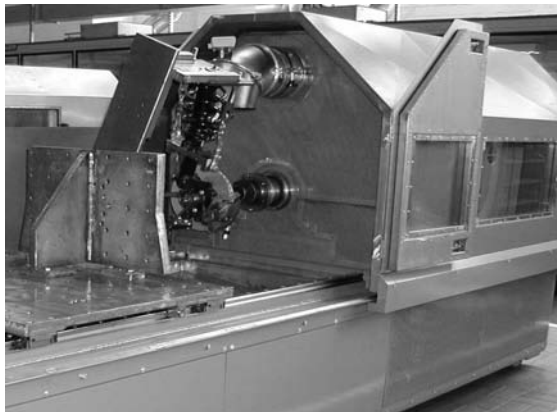


Figure 1

Dynamometer with test set-up.

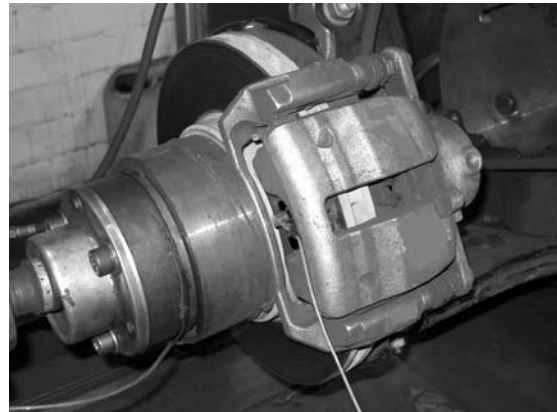


Figure 2

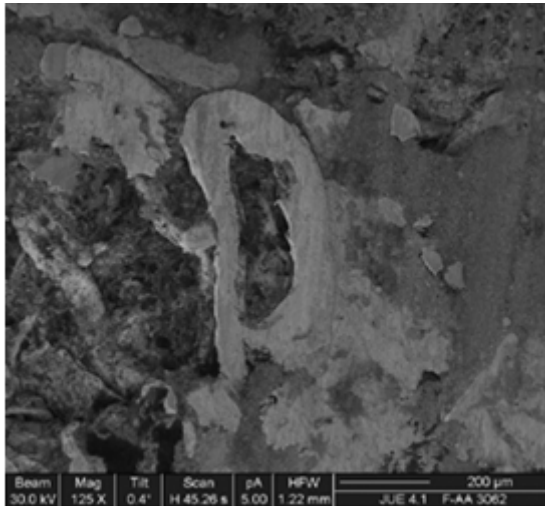
Accelerometer mounted on backing plate.

The friction noise and vibration data is obtained by an accelerometer mounted on the backing plate of the outer brake pad (Fig. 2). The sensor is an optimised piezoelectric type providing a high limiting frequency up to ca. 100 kHz in conjunction with a sample rate of the data acquisition above 200 kHz.

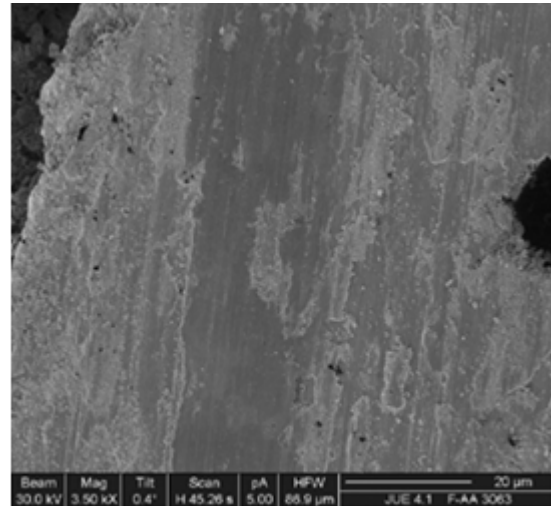
The suppression of unwanted high frequency electromagnetic radiation effects is assured by comprehensive EMC-compatible countermeasures. In addition, the galvanic isolation of the chassis earth of the test set-up, the dynamometer itself,

the data acquisition electronics, the dynamometer automation system as the trigger source and the isolation of the power electronics demanded further attention and arrangements.

The friction interface between the brake pad and the brake disc is formed amongst others by friction layers of accumulated and compacted wear debris shaping the surface roughness. Between these hard patches a composite representing more elastic areas (Figs. 3, 4) is bound.



----- ~ 1200 µm -----
Figure 3



----- ~ 90 µm -----
Figure 4

Surface of a brake pad section recorded with a focused ion beam (FIB) workstation. Steel fibre at pad surface (left) and patches of friction layer (right). Österle IWAAFC-I, Delhi, 2006

The acceleration signal of the sensor on the brake pad reflects the displacement of the backing plate and is primarily caused by the roughness and the irregularities of the contact while sliding on the brake disc. A typical spectral distribution of the signal is depicted in figure 5. Obviously, the audible range up to 16 kHz represents only a small portion of the acquired signal, the main information of the acoustic emission is found in the ultrasonic range. The estimation of the theoretically measurable scale of single irregularities reveals the necessity of a high acquisition time resolution: presuming $\sim 3\text{km/h}$ as a typical vehicle speed when friction induced squealing occurs, effects related to length-scales of about $1\text{ }\mu\text{m}$ can be detected only for sampling rates of at least about 200 kHz.

The sensitivity of the applied sensor strongly decays above 95 kHz. The use of other measuring principles in order to elevate the cut-off frequency is accompanied by other disadvantages or is even impossible because acoustic emissions in a high frequency range strongly abate over distance. In addition, rough environmental conditions inside the dynamometer test chamber render the operation of an optical laser-doppler-system in the ultrasonic range almost impracticable.

The exemplary spectral density distribution in figure 5 reflects the dynamic processes at the friction interface with its current properties at a certain time. The contribution over frequency changes typically not within one brake application and merely very slowly from one brake application to the next. Nevertheless, it may change completely after hundreds of applications. The capability of the applied acquisition method to measure contact interface characteristics seems to be validated by the shape of the distribution right before the brake application: the characteristic appearance of the frequency distribution does not show significant differences when a clamped or unclamped brake is considered, while it is

well known that the modal properties of the system do of course change significantly then.

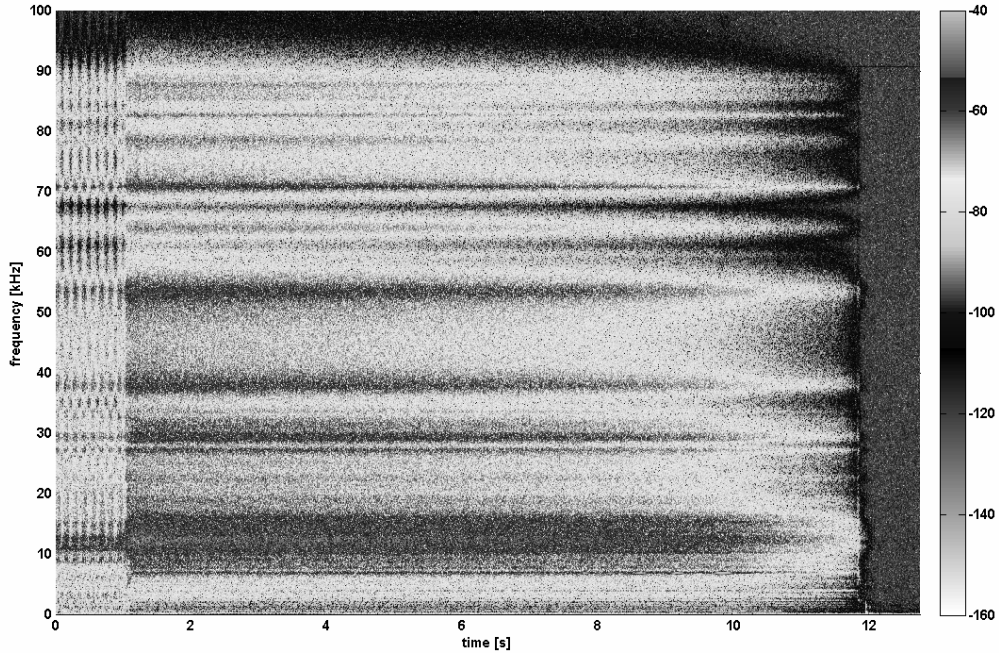


Figure 5

3. Recurrence Analysis

On the time scale of seconds the spectral analysis based on the broadband friction vibration data shows mainly steady-state behaviour in terms of the short time FFT spectra. Considering the characteristics of the friction contact with its rapidly changing friction processes – or to be more specific – the permanent reorganisation of the participating particles in contrast leads to the assumption that in the stationary overall contact mechanics micro-scaled particle respectively wear patch dynamics may be hidden.

As transformations into frequency domain always imply a certain averaging over short time events, the analysis of the data in time domain preserves all details of the acquired data.

To also reveal the dynamics due to micro-scaled particles, recurrence analysis turns out to be promising. Recurrence plots can be mathematically generated by determining, if a certain system state recurs (up to a threshold distance) at a later time [3]. Since the reference state in general also changes over time, this leads – based upon a temporal discretisation – to a recurrence matrix given by

$$R_{i,j}^{m,\varepsilon} = \Theta\left(\varepsilon - \|\vec{x}_i - \vec{x}_j\|\right), \quad x_{i,j} \in \mathbb{R}^m, \quad i, j = 1 \dots N,$$

where N is the number of considered states, ε_i is a threshold distance, and $\Theta(-)$ the Heaviside function. Without a fixed threshold distance and in order to illustrate the definite distances of the states the formulation

$$D_{i,j}^{m,i} = \|\vec{x}_i - \vec{x}_j\|$$

is useful. Examining the data on the basis of recurrence plots reveals strong disruptions and therefore non-stationarity on short time-scales (Fig. 6, 7). Apparently, the irregular micro-scale motions on these short time-scales leave their footprints in the recurrence analysis while in their entirety they result in a stationary spectrum on slower time scales.

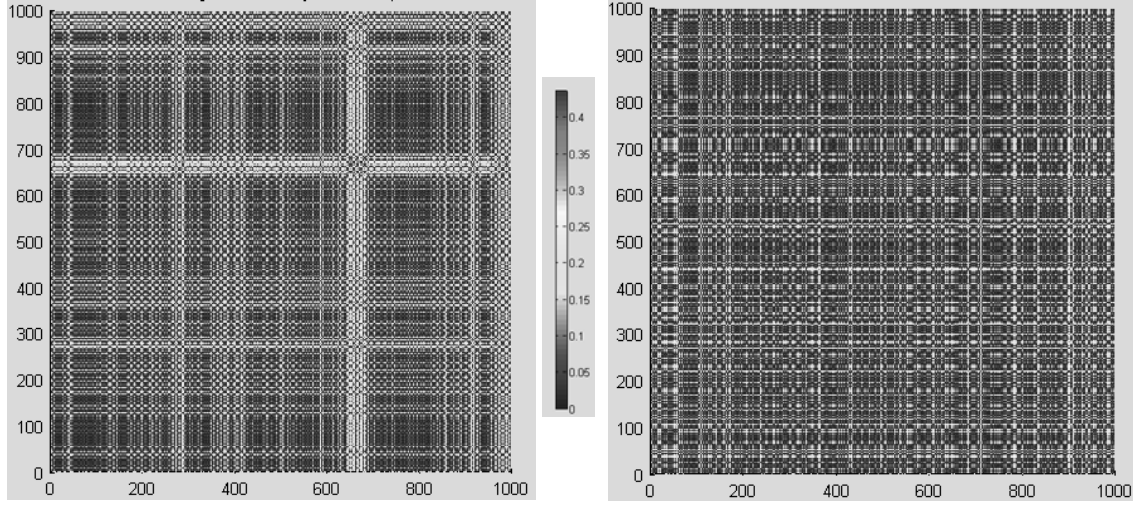


Figure 6, 7

Recurrence plots for two different system states: each calculated of 1000 samples (~5ms) of high sampled data. Dark areas represent small distances thus small changes near zero, white areas correspond to irregularities

The patterns emerging from recurrence analysis in the recurrence plots may be understood as a measure of the friction process – or to be more precisely – provide an image of the complex oscillations of the pad sliding on the disc. Of course, in the case of large-scale friction induced instability (through e.g. mode coupling), the dynamics of the system is dominated by the coherent large-scale vibrations of the participating parts and the recurrence analysis loses relevance: Due to the much higher vibration amplitudes of the system in squealing conditions the smaller amplitudes of the friction noise are somehow shadowed by the patterns of periodic signals. On the other hand, the characterization of the friction noise by numerical analysis of the oscillations passes into the description of mode coupling of the complete mechanical system when dominated by harmonic vibration.

4. Phase Space Reconstruction

The irregularities and non-linear disruptions of the high dimensional phenomena of the friction interface of brake pads and brake disc discovered by the recurrence analysis on short time scales result in almost steady-state behaviour in the spectral analysis in time scales of seconds. In other words, the irregular micro-scaled motions in their entirety apparently result in a stationary spectrum on slower time scales.

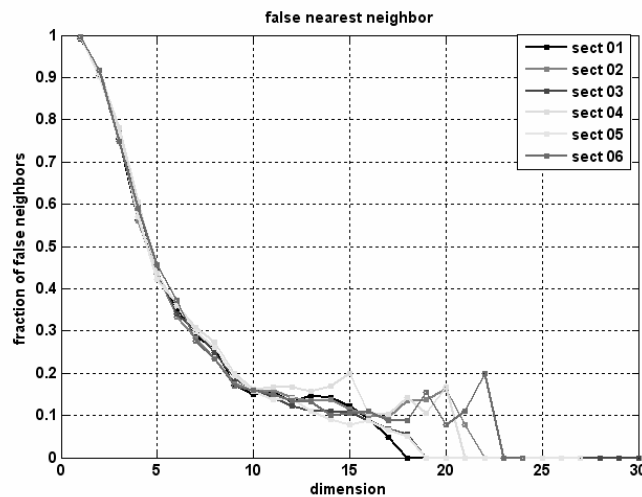
On account of this, the description of the high dimensional mechanics of the friction interface might be reduced respectively approximated by a lower order of dimensions if the overall dynamics shows signs of low-dimensional deterministic dynamics. To determine if this hypothesis is valid, phase space reconstruction techniques have to be applied [4]. In these approaches, a higher-dimensional state of the system is reconstructed from the available time-series data by so-called embedding techniques: e.g. from a single time-series successively measured data values may be grouped into a vector with a certain dimension, the so-called embedding dimension, representing the system state. It can then be shown that the temporal evolution of this new state vector reconstructs a possibly underlying high-dimensional dynamics, if the embedding dimension - and other reconstruction parameters - are chosen appropriately [5].

One capable method to estimate the minimal sufficient embedding dimension is the *false nearest neighbour* method [Kennel]. Basically the method determines, if the trajectories in the reconstructed system have been unfolded sufficiently.

The idea of this algorithm is to look for the nearest neighbour of each point in the time series in an m -dimensional phase space. The criterion for a point to be a false neighbour with a given heuristic threshold R_{tot} and the distance in phase space R_d is then

$$\frac{|x_{i+1} - x_{j+1}|}{R_d(x_i, x_j)} > R_{tot} \quad x_{i,j} \in \mathfrak{R}^m \quad i, j = 1 \dots N$$

The requirement for a high enough embedding is fulfilled when the fraction of points being false nearest neighbours is sufficiently small. Figure XX shows an example of the results calculated for the friction vibration signals, where six different data sections within a brake application are observed. Surprisingly the fraction of the false nearest neighbours decreases rapidly with growing embedding dimension. The estimation of dimensionality, respectively the phase space reconstruction therefore indicates that a strange attractor with a dimensionality of about 10 – 12 seems to be hidden in the data. Evidently, noise is superimposed on this irregular deterministic dynamics.



Surprisingly, even with varying conditions in terms of brake system parameters, the appearance of a low-dimensional strange attractor underlying the data seems to be generic.

5. Summary

The description of the high dimensional phenomena of the friction interface in terms of short time FFT spectra shows nearly steady-state behaviour even with varying system parameters, e.g. such as sliding velocity. This seems to be a kind of integration of the complex interface mechanics. To get a deeper insight in these short-time and small length-scale effects the vibration signals are sampled with high frequencies and depicted with recurrence plots which reveal strong disruptions in terms of the vibration amplitude but also laminar phases of nearly no displacements. The non-linear phase space reconstruction indicates a low-dimensional deterministic kernel of the underlying dynamics and yields an estimation of its corresponding dimensionality.

6. Outlook

As an extension of recurrence analysis, the recurrence quantification analysis (RQA) quantifies the small-scale structures of recurrence plots, which in turn yield measures for the duration and the number of the recurrences. The measures of the RQA allow the description of large data sets and the correlation of the RQA indices with other system properties such as squeal propensity. This will enlighten the question if the dynamic mechanism on different length-scales can be correlated with dynamic properties observable in time-series analysis and might provide the prediction of the noise behaviour of a brake system based on friction interface characterization and characteristic results from non-linear time-series analysis.

The estimation of the maximal Lyapunov exponent iteration with its indication of exponential divergence possibly will support the assumption of the presence of a strange attractor derived from the phase space reconstruction.

7. References

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