

Comparing Time Series from Experiments with and without Spiralling

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Abstract

In this paper we compare data from BTA deep-hole drilling experiments conducted according to an experimental design, which had to be repeated due to the development of spiralling in all experiments in the first repetition. We compare the time series of the drilling torque and the bending moment with respect to the development of the maximal Lyapunov-Exponent and the overall relevant frequencies and the relevant frequencies on sections of the process.

1 Introduction

The aim of the project is to analyse and model the BTA deep-hole drilling process. This process is used in mechanical engineering for the production of long and slender bore holes. The flexibility of the tool-boring bar assembly leads to the development of to dynamic disturbances, chatter and spiralling. In this paper we focus on spiralling. Spiralling leads to a severe workpiece impairment because it produces holes with regular lobes which slowly turn around the center of the hole and increase the hole diameter significantly.

The data we use was produced in two runs of an experimental design which was constructed to test the effect of the Lanchester damper on the process. In the first run of the design spiralling occurred at all settings of the design parameters. When checking the machine and tool for possible reasons it turned out that the guiding pads were excessively worn. Replacing the guiding pads by new ones and repeating the design completely no spiralling was observed in any of the experiments. Also the Lanchester damper was optimally positioned because no chatter was observed as well.

Since the Lyapunov exponent was able to detect chatter prematurely in the drilling torque (Busse, 2003), we apply it here to the data of the drilling

torque and the data of the bending moment and compare the results from the two runs of the experimental design. Another good procedure for the investigation of the data from experiments with chatter was the detection of relevant frequencies (Theis et al., 2004) so we applied this here as well to the named time series.

The paper is organised as follows: after a short description of the experimental setup in Section 2 we show some spectrograms of the data for a better insight into the behaviour of the process in Section 3. Section 4 gives a short description of the used methods. In Sections 5 and 6 we present the results of our investigations. We finally summarize our results in Section 7.

2 Experimental Setup

The experimental setup was essentially the same as described in Theis et al. (2004) but we replaced one of the measurements of structure-borne sound by measurements of the radial acceleration of the boring bar in one direction. Additionally we used the Lanchester damper positioned at an optimal point to damp the determined chatter frequencies. Figure 1 shows the machine with the positions of the measurement devices and the damper. It should be noted that the moments are measured on the far end of the boring bar and therefore all signals are influenced by the damper.

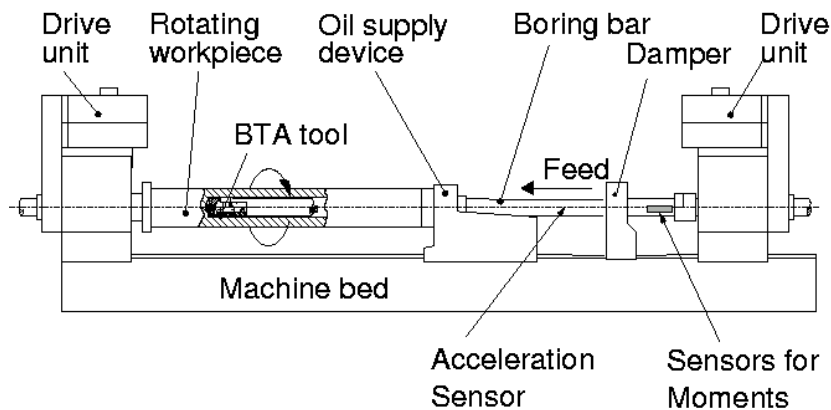


Figure 1: Experimental setup with the Lanchester damper and positions of the measurement devices.

Table 1 gives the central-composite design in the feed f and the cutting speed v_c which was repeated after recognizing the wear of the guiding pads. The oil-flow rate is only given for completeness since it was varied in our first experimental design.

	f mm	v_c m/min	\dot{V} l/min	Spiralling
1	0,185	60	300	yes
2	0,139	111	300	yes
3	0,139	69	300	yes
4	0,231	111	300	yes
5	0,120	90	300	yes
6	0,185	120	300	yes
7	0,231	69	300	yes
8	0,250	90	300	yes
9	0,185	90	300	yes
10	0,185	90	300	yes
11**	0.185	90	300	no

Table 1: Experimental design used for the investigation; (**) New guiding pads, otherwise reptition of experiment 10 \implies no spiralling.

3 Spectrograms of the Drilling Torque and the Bending Moment

First of all we explored the behaviour of the drilling torque and the bending moment by means of the spectrogram and compared especially the frequencies below 2200 Hz since these included the most interesting features in the case of chatter. Figures 2 and 3 show the spectrograms of the drilling torque and the bending moment, resp., of experiment 10 which is one of the repetitions on the center point in the experimental design.

For the drilling torque in Figure 2 the overall pattern looks very similar. After the guiding pads leave the starting bush the spectrograms reveal an excitation close to the frequency 1188 Hz which decreases totally before 200mm. Later in the process frequencies close to 500 Hz become more prominent in this experiment. Very similar observations were made on the other spectrograms of the drilling torque: the structures in the spectrograms are more obvious in the case of spiralling than without spiralling but they are more or less the same. The difference in drilling depth results from the fact that we used an automatic procedure to detect start and end of the drilling process which is slightly effected by the low level of the signals especially in the case without spiralling. We checked whether the start is detected correctly and besides small differences to a manual detection this was the case.

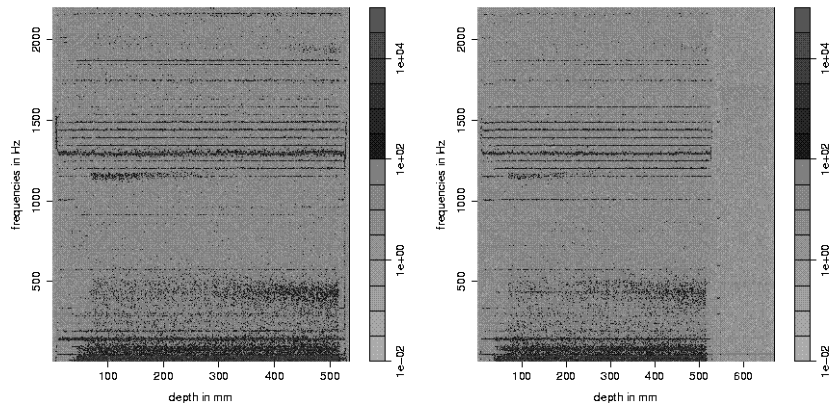


Figure 2: Spectrograms of the drilling torque, Experiment 10 left: with spiralling; right: no spiralling

The spectrograms of the bending moment in Figure 3 are also quite similar with respect to the general structure of the significant frequencies and their variation. At first sight one gets the impression that the frequencies are expressed clearer in the case of no spiralling but this is due to the fact that the variance in the data without spiralling is slightly lower as can be seen from the scales on the right hand side of the spectrograms where the start of the dark shades has a lower value for the data without spiralling. Here again the only true difference lies in the low frequencies which are more prominent for the data with spiralling.

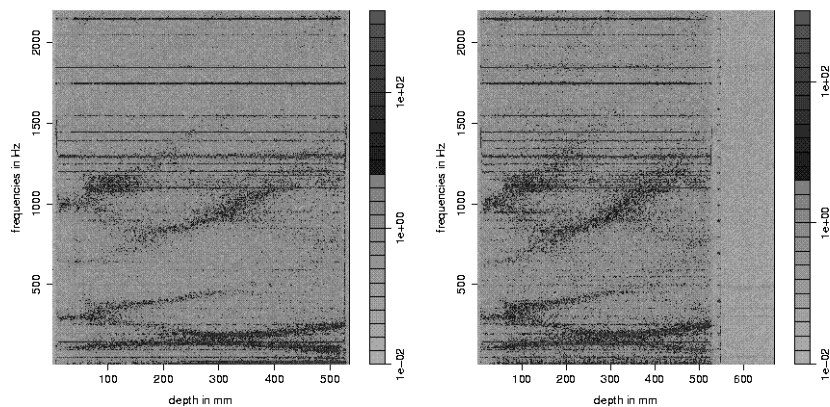


Figure 3: Spectrograms of the bending moment, Experiment 10 left: with spiralling; right: no spiralling

Finally we checked single spectra for quantitative differences. In the case of the drilling torque none could be found as shown in Figure 4.

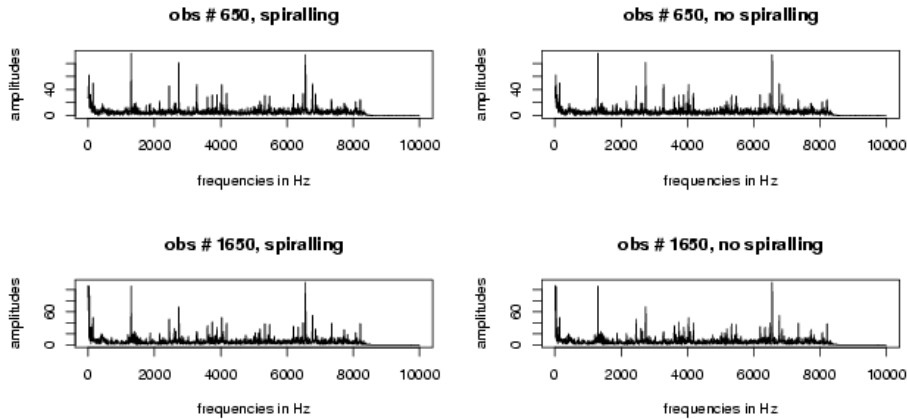


Figure 4: Spectra of the drilling torque at different depths for experiment 10 with and without spiralling: no obvious differences visible.

4 Methods

4.1 Lyapunov exponent

In connection with the description and the analysis of time series the Lyapunov exponent can be used for the determination of the predictability of time series (Busse et al., 2001) or to discriminate stable and unstable processes (Busse and Weihs, 2004). The Lyapunov exponent is a feature of the asymptotic behaviour of the underlying process. If the Lyapunov exponent is greater than 0, an unstable, non-predictable process is described. If the Lyapunov exponent is smaller than 0, the stable process is represented.

In the case of chatter we identified the change of non-chatter and chatter by the Lyapunov exponent (Busse, 2003). For the identification of spiralling we use the Lyapunov exponent to find possible different behaviour of the underlying process.

4.2 Relevant Frequencies

We used the method to determine relevant frequencies as described in Theis (2004) first on the complete time series of the drilling torque and the bending moment to determine the generally present frequencies. Then we splitted the

time series into subsections which are partly motivated by knowledge about the machine-assembly and partly simply chosen regularly.

To define relevant frequencies we tested the frequencies for significance on a 95% level in all situations. In the case of the drilling torque we asked only for significance in 20% of the spectra within one experiment but this in 90% of the experiments. This was done to ensure that frequencies dominating shorter phases, e.g. the starting phase, in the process appear in the relevant frequencies. For the bending moment the criteria was slightly harder asking for 40% significant observations within the experiments and this in 80% of the experiments.

4.3 Relevant Frequencies on Sections of the Process

We divided the process into sections which are motivated by our results on chatter (cf. Theis et al. (2004)). The first section consists of the drilling depth 0-35 mm because the guiding pads are then still in the starting bush and therefore all possible movements are strongly damped. The second section is 35-110 mm because the process showed a general tendency to change its behaviour in this section. Then we splitted the rest of the drilling depth into the sections 110-150 mm and thereafter into 50 mm sections because no typical sections could be derived from the process behaviour observed so far. On these sections we determined the relevant frequencies as described before with the following settings: for the drilling torque the criteria are harder than in the general case, asking for 40% significant observations within the experiments within one section and this again for 80% of the experiments. For the bending moment already 20% of the observations sufficed for relevance because as is obvious in Figure 3 the bending modes change with the process. For the general relevance over all experiments again 80% relevant appearances in all experiments were necessary.

We also tested harder conditions but in most cases this led to no relevant frequencies at all.

5 Drilling Torque

5.1 Lyapunov exponent on Sections: Drilling Torque

From the drilling torque it is not possible to discriminate spiralling and no spiralling. In both cases the Lyapunov exponent describes an unstable, non predictable process. Even if the values of the Lyapunov exponent in experiment 6 (with chatter) disagree to the other experiments, it is not possible

to discriminate the spiralling and the no spiralling cases. Even if the values disagree, no significant differences are verifiable.

For a better impression we report the results for experiment 6 of both runs in Table 2 on two sections each from the start and the end of the experiment.

section in mm	Lyap exp.: first run	Lyap exp.: second run
35–110	1.047	0.0453
110–150	1.097	0.295
300–350	0.976	0.265
450–500	0.986	0.295

Table 2: Lyapunov exponents for different sections of the drilling torque.

All the Lyapunov exponents are greater than 0 and therefore indicate an instable process in all situations. The different size of the exponents may be due to differences in the strength of the signals or the amount of noise.

5.2 Generally Relevant Frequencies of the Drilling Torque

For the drilling torque the most interesting result on the generally relevant frequencies is the fact that in the case of spiralling the number of relevant frequencies (38) is reduced compared to the case of no spiralling (78). Only the frequencies 3300.78 Hz and 6875 Hz are present in the case of spiralling but not in the case of no spiralling. Additionally it is obvious that all frequencies < 65 Hz are generally found relevant under the given conditions. Table 3 reports the common relevant frequencies, while Table 4 reports the frequencies only found in the case of no spiralling.

[1]	4.88	9.77	14.65	19.53	24.41	29.30
[7]	34.18	39.06	43.95	48.83	53.71	58.59
[13]	63.48	83.01	1450.20	1748.05	1850.59	3266.60
[19]	3271.48	3276.37	3281.25	3286.13	3291.02	3295.90
[25]	3549.80	3652.34	5346.68	5449.22	6552.73	6557.62
[31]	6562.50	6567.39	6572.27	6577.15	6582.03	6870.12

Table 3: Frequencies in Hz found relevant for the drilling torque in all experiments – with or without spiralling.

Interesting about the additional frequencies in Table 4 is that they are mainly between 85 and 500 Hz where this range is totally void of relevant frequencies in the case of spiralling. This could be due to a stronger and more stable excitation of the low frequencies which could be seen in the spectrograms.

[1]	68.36	73.24	78.12	87.89	92.77	97.66
[7]	102.54	107.42	112.30	117.19	122.07	146.48
[13]	151.37	156.25	180.66	190.43	297.85	458.98
[19]	468.75	478.52	488.28	498.05	507.81	517.58
[25]	532.23	1752.93	3251.95	3349.61	3647.46	3950.20
[31]	4150.39	4550.78	5048.83	5151.37	5351.56	5751.95
[37]	6049.80	6547.85	6850.59	6865.23	7250.98	7548.83

Table 4: Frequencies found relevant for the drilling torque only in the case of no spiralling.

Since the experiments were initially conducted to check whether the Lanchester damper is able to remove the chatter frequencies determined (cf. e.g. Theis et al. (2004)) it should be mentioned that these frequencies, 234 Hz, 703 Hz and 1188 Hz have been removed completely. This proves that the damper in the right position is able to damp oscillation of the torsional eigen-frequencies effectively. But as mentioned in e.g. Theis (2004) it is not always feasible to reach the most effective position with the damper since it is restricted to the free part of the boring bar.

5.3 Relevant Frequencies on Sections: Drilling Torque

Looking at Figures 5 and 6 which show histograms of the frequencies found relevant on the sections for each of the experiments, it is hard to make out the difference between the two. Only for the last three sections a difference is visible: the frequencies just below 500 Hz are chosen more often for the experiments without spiralling. At close inspection there are more relevant frequencies < 50 Hz for the case of spiralling than in the case with no disturbance.

The situation becomes more obvious when looking at Figures 7 and 8 which show the frequencies found relevant when relevant means not just significant in most of the observations within one experiment but also in 80% of all experiments. Here it becomes obvious that the low frequencies (5-10 Hz) are relevant right from the start in the case of spiralling while

without spiralling they become relevant only after 110 mm. In the case of no spiralling the frequencies of 15-20 Hz are more important. Furthermore it can be seen that in the case of no spiralling there are more frequencies found relevant while in the case of spiralling the process seems to be completely dominated by the low frequencies.

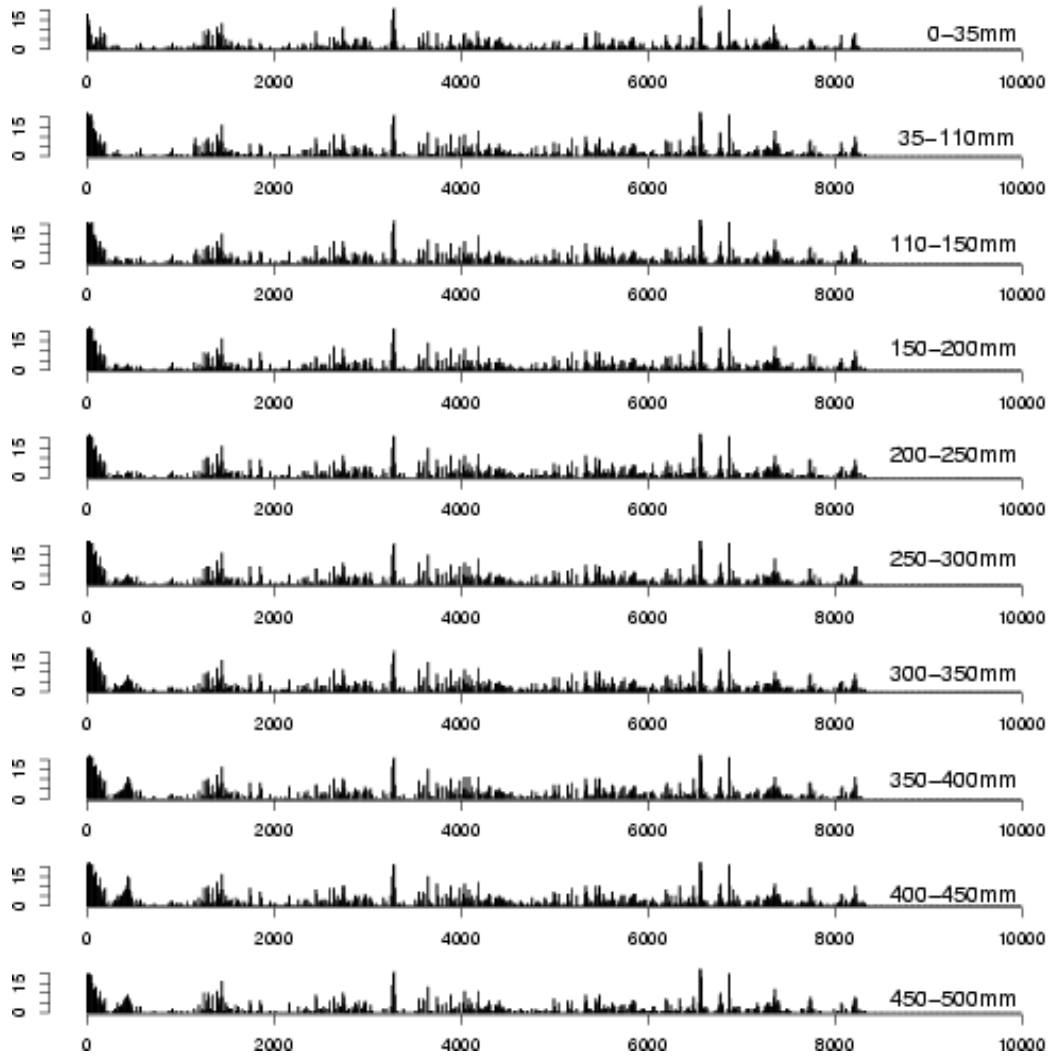


Figure 5: Histograms of relevant frequencies on parts of the drilling depth (0-35mm, 35-110mm, 110-150mm, 50mm sections up to 500mm) for the drilling torque on the experiments with spiralling.

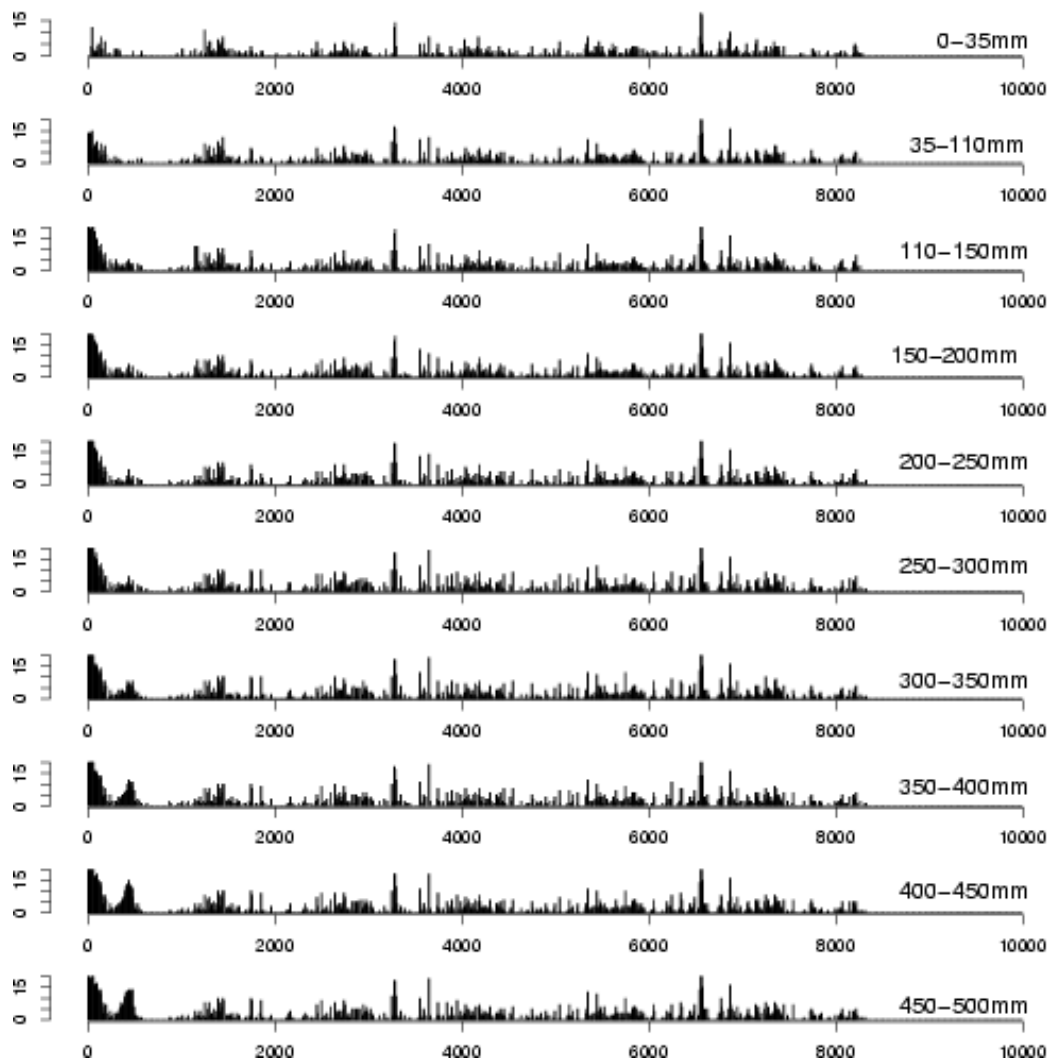


Figure 6: Histograms of relevant frequencies on parts of the drilling depth (0-35mm, 35-110mm, 110-150mm, 50mm sections up to 500mm) for the drilling torque on the experiments without spiralling.

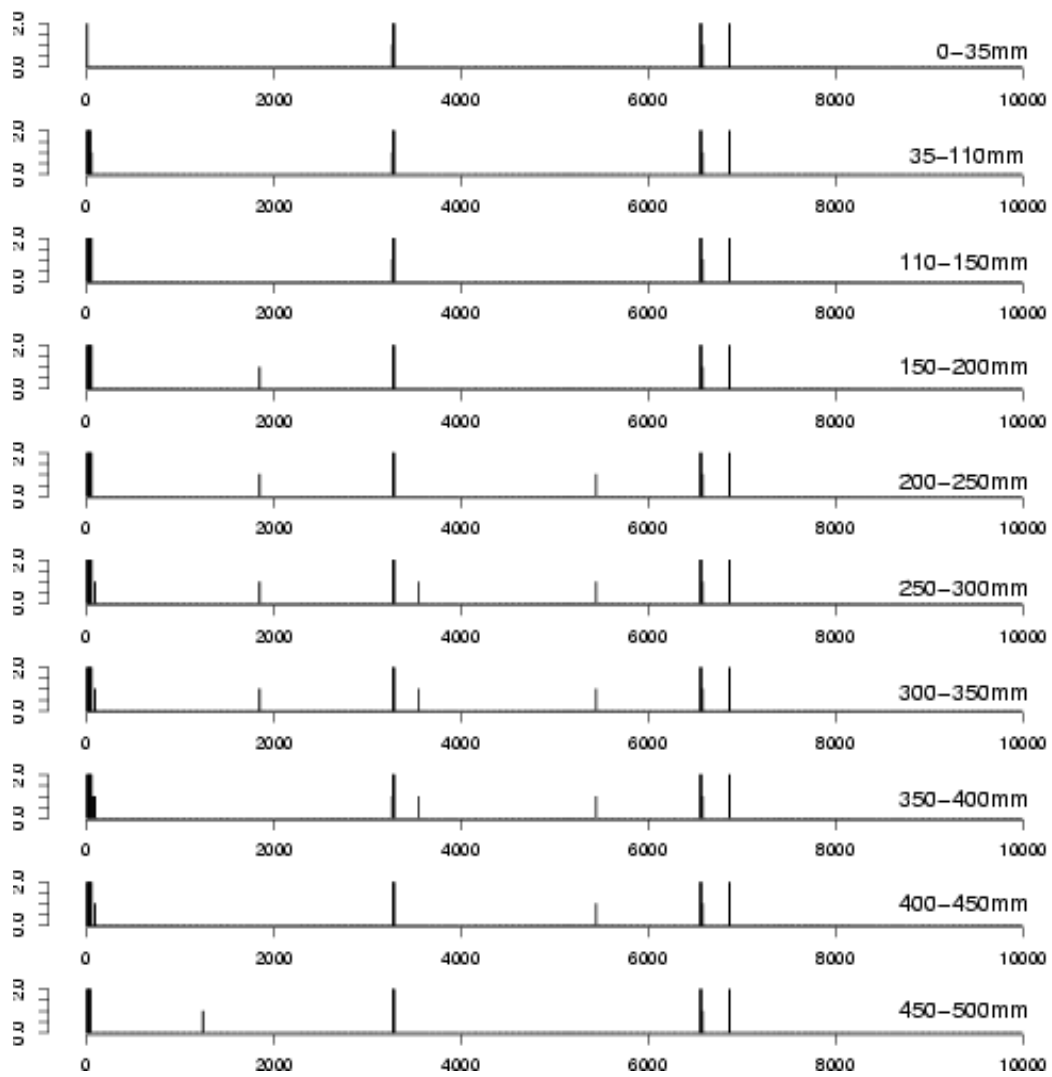


Figure 7: Histograms of relevant frequencies on parts of the drilling depth (0-35mm, 35-110mm, 110-150mm, 50mm sections up to 500mm) in 80% of the experiments for the drilling torque on the experiments with spiralling.

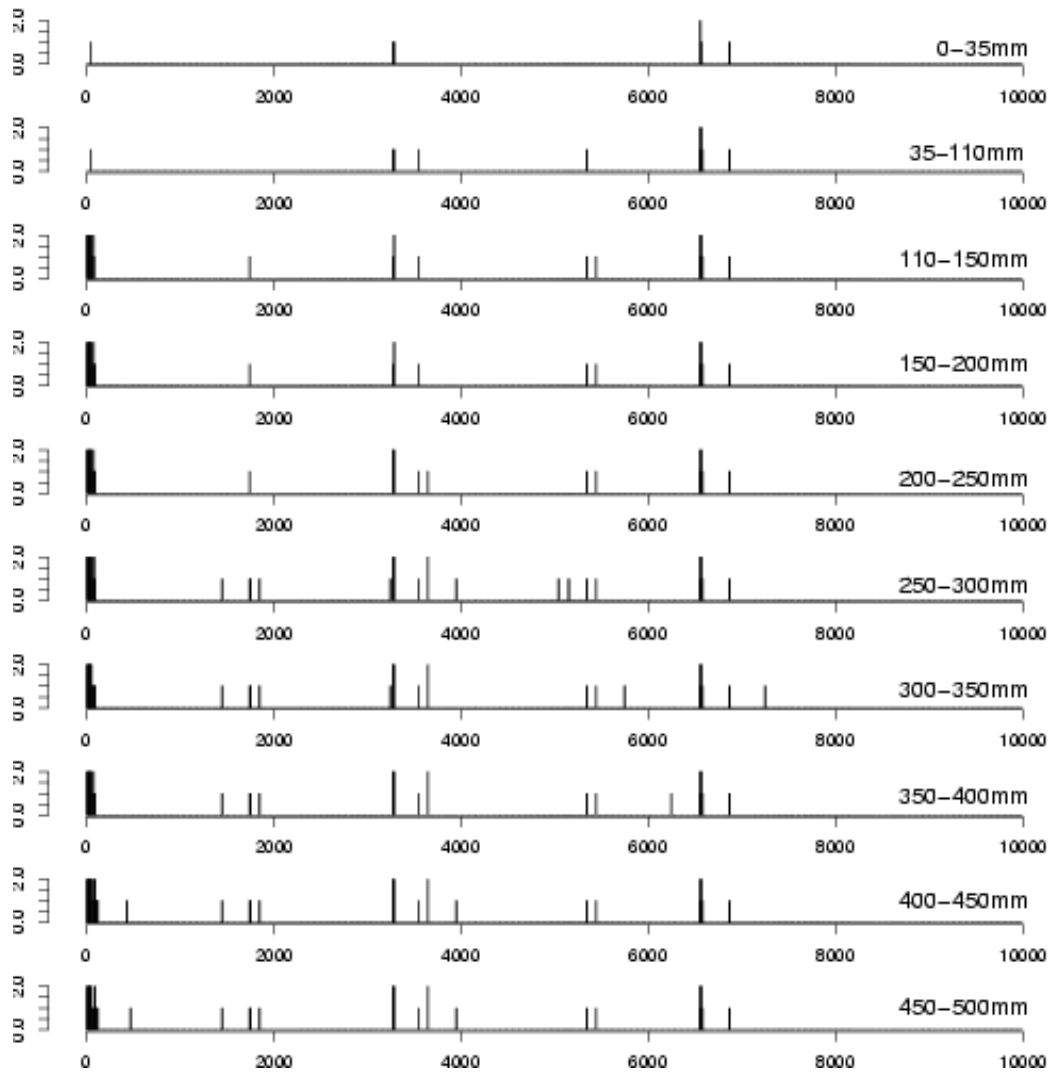


Figure 8: Histograms of relevant frequencies on parts of the drilling depth (0-35mm, 35-110mm, 110-150mm, 50mm sections up to 500mm) in 80% of the experiments for the drilling torque on the experiments without spiralling.

6 Bending Moment

6.1 Lyapunov exponent on Sections: Bending Moment

We applied the method of Lyapunov exponent estimation to the time series of bending moments. It is not possible to classify the time series in experiments with spiralling and without spiralling by the Lyapunov exponent. Also the tests made to identify missclassifications show possible differences.

For a better impression we report the results for experiment 10 of both runs in Table 5 on two sections each from the start and the end of the experiment.

section in mm	Lyap exp.: first run	Lyap exp.: second run
35–110	1.105	0.284
110–150	1.082	0.239
300–350	0.298	0.246
450–500	0.298	0.281

Table 5: Lyapunov exponents for different sections of the bending moment.

Again all Lyapunov exponents are greater than 0 and so indicate again a generally instable behaviour of the process.

6.2 Generally Relevant Frequencies of the Bending Moment

For the bending moment we found only 51 and 40 relevant frequencies without and with spiralling, respectively. This is to be expected since it is known that the bending modes change with the hole depth (Gessesse et al., 1994). So only constantly excited frequencies will be found by asking for generally relevant frequencies. The most interesting frequencies generally relevant are the frequencies near 125 Hz because they are quite low and are not directly connected to either the range of the revolutionary frequency or something like an oscillation introduced by the electrical devices.

One frequency is also surprising, this is the frequency 2148.44 Hz which was found in the drilling torque to be a good discriminator for the prediction of chatter right after the guiding pads leave the starting bush (Theis, 2004).

[1]	4.88	9.77	48.83	122.07	126.95	146.48
[7]	249.02	1450.20	1547.85	1748.05	1752.93	1850.59
[13]	2148.44	2153.32	2348.63	2451.17	3247.07	3251.95
[19]	3276.37	3281.25	3286.13	3291.02	3295.90	3349.61
[25]	3549.80	3588.87	3642.58	3647.46	3652.34	3847.66
[31]	3852.54	3950.20	4150.39	4248.05	4550.78	5048.83
[37]	5151.37	5351.56	5449.22	5649.41	5751.95	5952.15
[43]	6049.80	6352.54	6557.62	6562.50	6567.38	6850.59
[49]	6870.12	7250.98	7451.17			

Table 6: Generally relevant frequencies of the bending moment in the case of no spiralling.

[1]	4.88	9.77	48.83	122.07	126.95	1250.00
[7]	1450.20	1748.05	1752.93	1850.59	2148.44	2348.63
[13]	2451.17	3251.95	3276.37	3281.25	3286.13	3291.02
[19]	3295.90	3349.61	3549.80	3647.46	3652.34	3950.20
[25]	4150.39	4248.05	4550.78	5048.83	5151.37	5351.56
[31]	5449.22	5649.41	6049.80	6557.62	6562.50	6567.38
[37]	6870.12	6875.00	7250.98	7451.17		

Table 7: Generally relevant frequencies of the bending moment in the case of spiralling.

6.3 Relevant Frequencies on Sections: Bending Moment

Compared to the drilling torque more relevant frequencies are generally found in the sections for the bending moment. Again the differences between spiralling and no spiralling are hard to discern but looking at the low frequencies the differences become apparent. As for the drilling torque the low frequencies < 50 Hz are relevant right from the start of the process in the case of spiralling. They dominate the process in the last three sections quite clearly so that there are less relevant frequencies close to 1000 Hz compared to the processes with no disturbance.

The pattern becomes again much clearer when relevance is further restricted to the frequencies which are found relevant in at least 80% of the experiments. In the histograms in Figures 11 and 12 it becomes quite obvious that the frequencies above 2000 Hz are of minor interest since they are not

much affected by spiralling. What is obvious from these histograms, is the slow movement of the relevant frequencies over time near 1000 Hz. The most striking feature of the histogram for the experiments with spiralling is the total lack of relevant frequencies between 500 Hz and ca. 900 Hz compared to the case without spiralling.

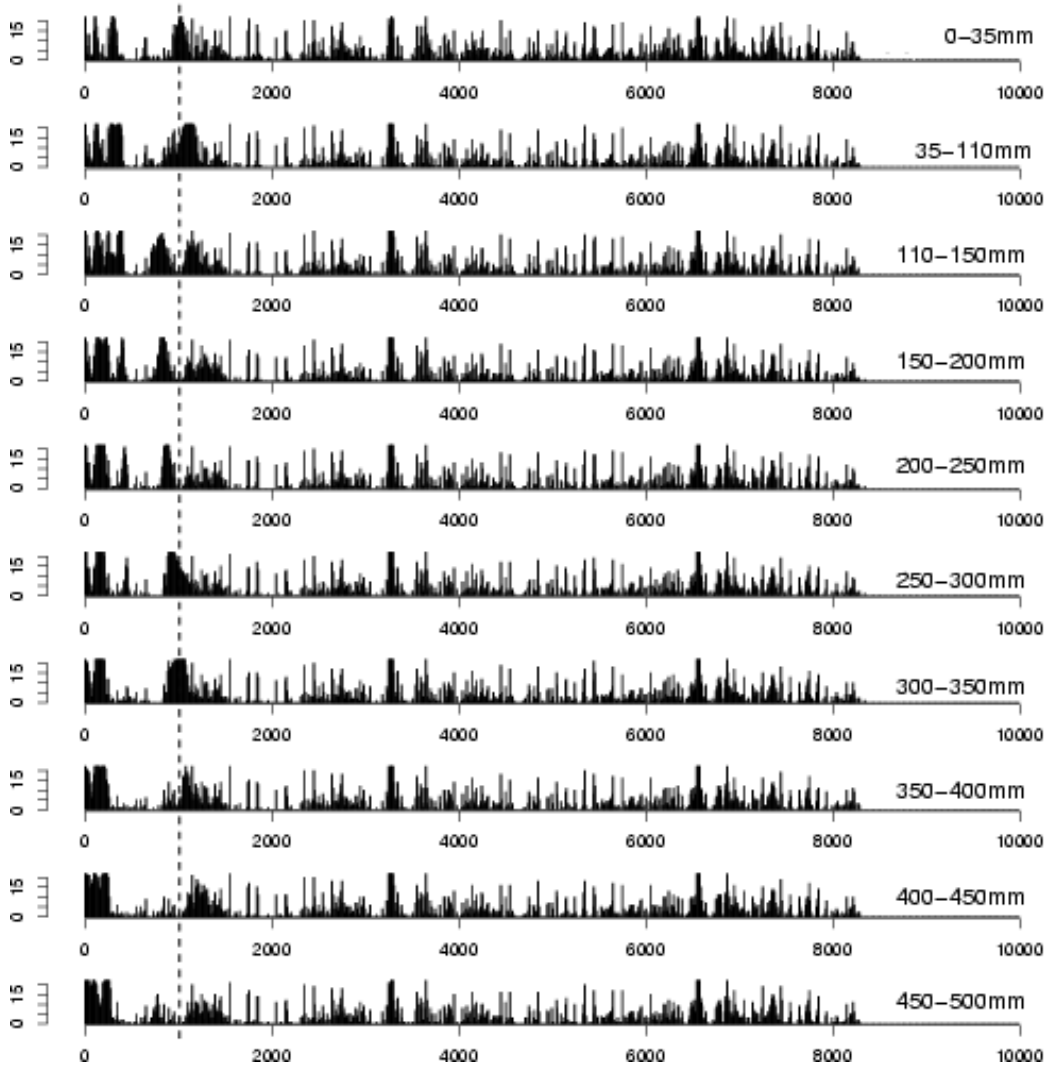


Figure 9: Histograms of relevant frequencies on parts of the drilling depth (0-35mm, 35-110mm, 110-150mm, 50mm sections up to 500mm) for the bending moment on the experiments with spiralling.

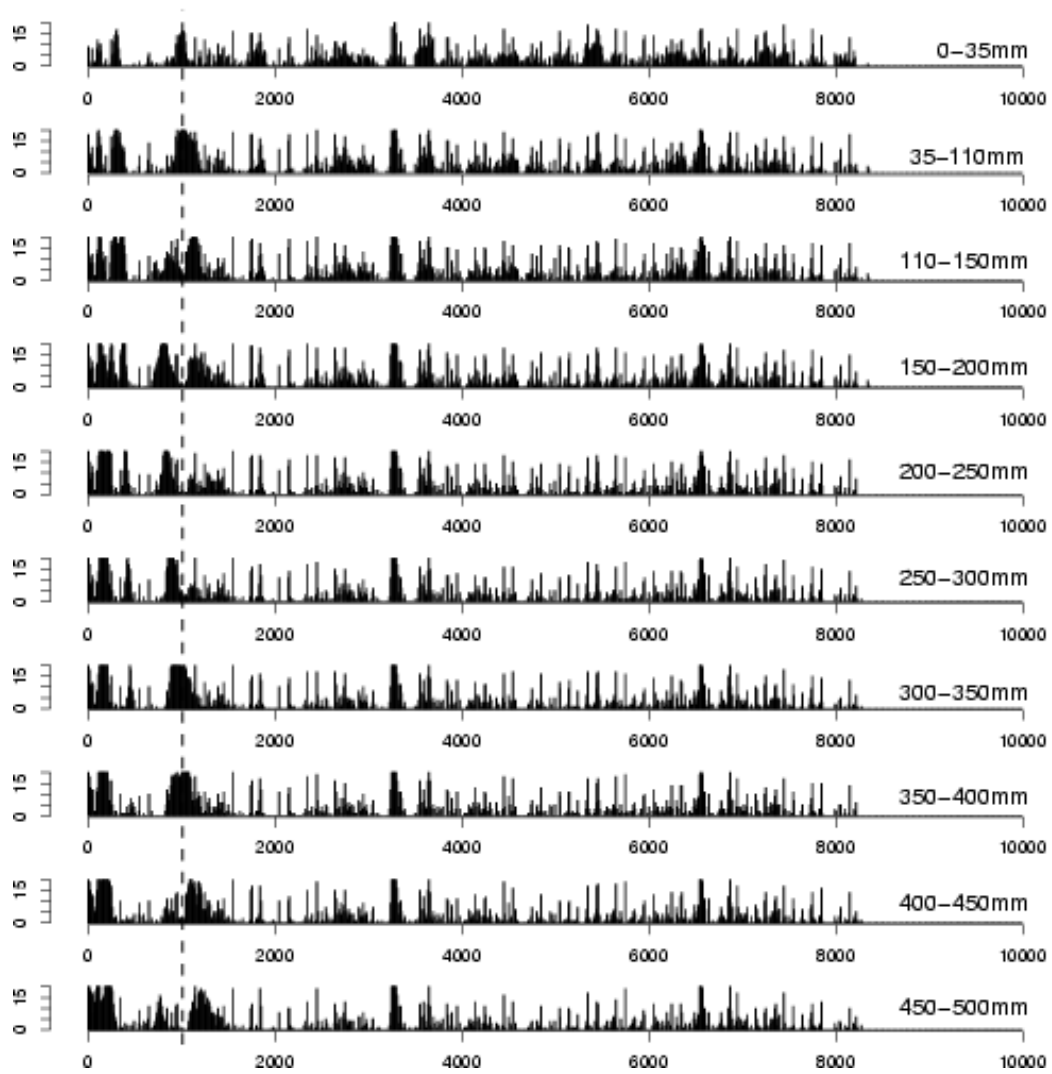


Figure 10: Histograms of relevant frequencies on parts of the drilling depth (0-35mm, 35-110mm, 110-150mm, 50mm sections up to 500mm) for the bending moment on the experiments without spiralling.

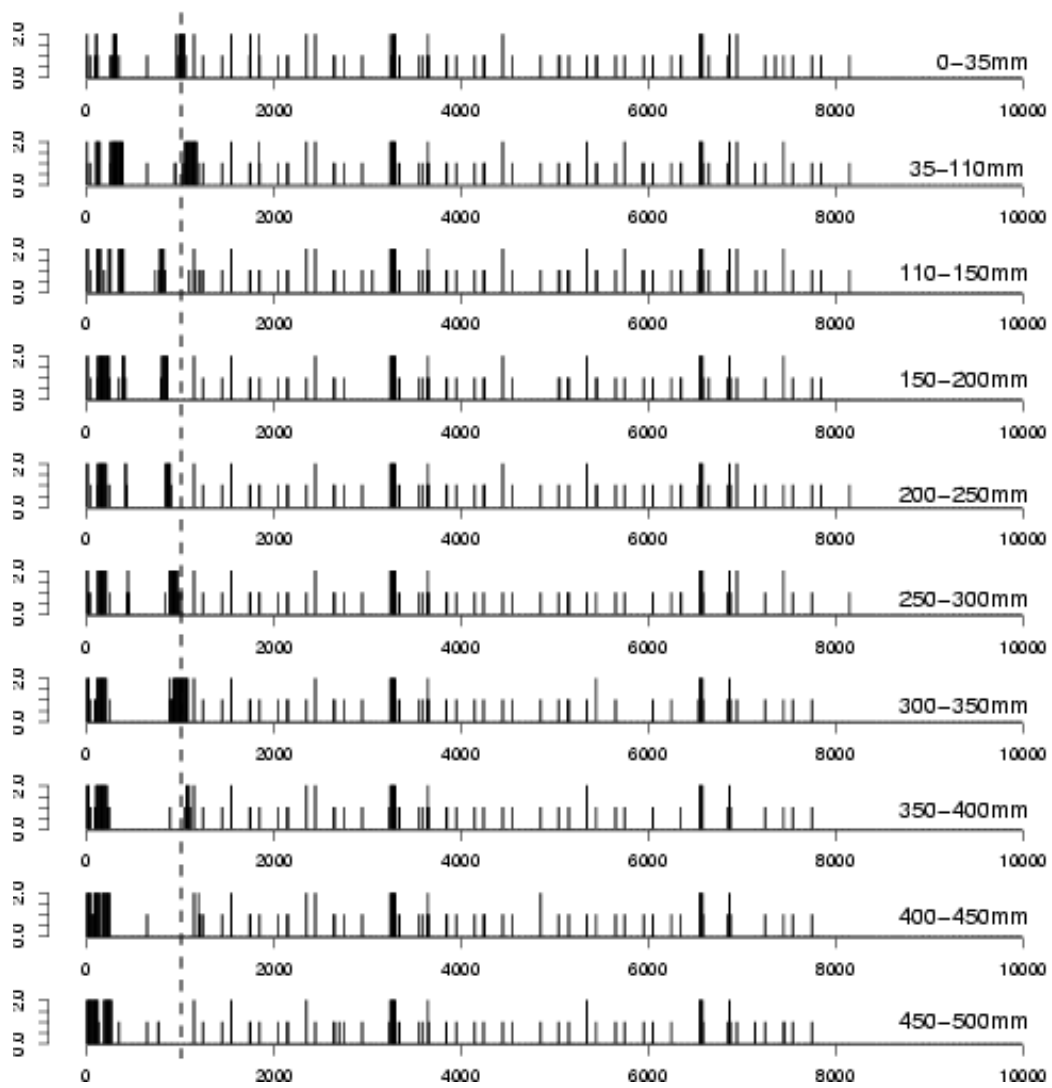


Figure 11: Histograms of relevant frequencies on parts of the drilling depth (0-35mm, 35-110mm, 110-150mm, 50mm sections up to 500mm)in 80% of the experiments for the bending moment on the experiments with spiralling.

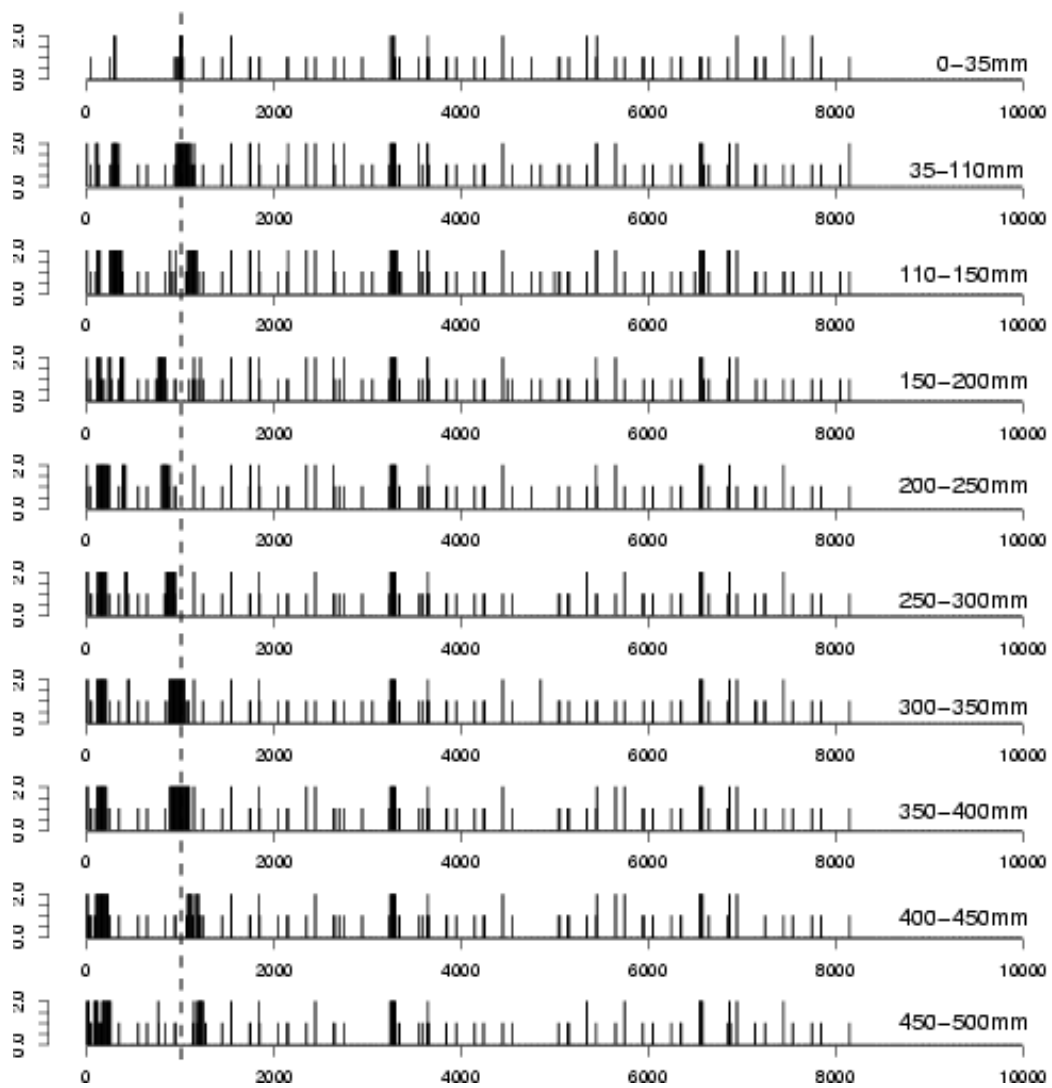


Figure 12: Histograms of relevant frequencies on parts of the drilling depth (0-35mm, 35-110mm, 110-150mm, 50mm sections up to 500mm) in 80% of the experiments for the bending moment on the experiments without spiralling.

7 Conclusions

The spectrograms we considered first as a descriptive analysis of the data from the experiments with and without spiralling (Figures 2 and 3) displayed only very slight differences in the drilling torque and the bending moment for the experiments. Comparing the spectra of the drilling torque in Figure 4 even less differences can be found. The only true difference in all

spectral analyses was the importance of the very low frequencies right from the start of the experiment in the case of spiralling. This was also true for the determination of the relevant frequencies.

The evaluation of the Lyapunov exponents showed no significant differences between the time series of the experiments with or without spiralling. They generally indicated an instable process.

From these investigations no sensible measurement can be derived for the detection of spiralling from the development of the used time series of the drilling torque and the bending moment. The relevance of the very low frequencies right from the start of the experiments points to a disturbed start of the process which either influences the rest of the process or further increases liability to develop instable process behaviour.

A possible reason for the failure to detect significant differences between the data with and without spiralling is the fact that the sensors for the investigated time series were placed behind the Lanchester damper which reduces the signal amplitude. So possibly the signals differed in their amplitudes in front of the damper but were restricted by the effect of the damper. This would also explain why certain frequencies are relevant for the data without spiralling but are not relevant when spiralling occurs. In the case of spiralling the energy is removed from these frequencies and they are therefore not relevant but the limiting effect of the damper makes it impossible to detect the additional energy in the frequencies important for spiralling. Therefore, placing the sensors in front of the damper and repeating the experiments with spiralling may lead to a deeper insight into the problem.

Acknowledgment

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