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Transient vibro-acoustic analysis of squeal events based on the experimental bench FIVE@ECL

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Abstract

The proposed study investigates the transient and stationary non-linear vibrations and acoustic phenomena occurring during the squeal phenomenon. Experiments are performed on the test bench Friction-Induced Vibration and noiseE at Ecole Centrale de Lyon (FIVE@ECL).

The first major contribution of the study is to demonstrate the ability of this test bench to reproduce transient squeal events for a given operational condition, allowing to conduct a thorough and robust study on the physical understanding of transient vibration and acoustic squeal events. The second main contribution is to discuss the potential links between the emergence of vibrations on the two pads, the disc and the caliper, and the squeal noise in near-field and far-field.

Keywords: friction-induced vibration, squeal noise, transient squeal events, experimental benchmark FIVE@ECL

1. Introduction

The subject of friction-induced vibrations and squeal noise is considered as one of the main issues of industrial brakes design. Understanding the physical phenomena linked to brake squeal is not obvious since it involves and requires a good overview of many scientific fields, such as structural dynamics, acoustics, tribology or thermodynamics. Generally speaking, squeal noise generated by friction induced vibration leads to a loud and annoying noise as well as a feeling of poor quality for the users. Reviews providing an understanding of this phenomena of friction-induced vibration as well as descriptions of potential mechanical mechanisms and physical factors that may be involved in brake squeal can be found in [1, 2, 3, 4, 5].

From an experimental point of view, both industrial and academic test rigs have been developed in order to propose contributions for a better understanding of the phenomena of brake squeal, as well as to investigate which physical phenomena could be the cause of the brake noise. For example some rely on research more focused on friction-induced vibrations [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17], while others study the subject via thermal considerations [18, 19] or a tribological point of view [20, 21, 22, 23, 24, 25]. On the other hand, some researchers [23, 26, 27, 28] are also interested in dealing with the problem of brake squeal by considering additionally the problem of acoustic radiated noise due to friction-induced vibration or roughness at the frictional interface. Nevertheless, in most cases, only one microphone is used for squeal noise measurement, except for studies specifically dedicated to acoustic holography on brake squeal in order to measure the disc motion and the associated traveling waves [29, 30]. Thereby a specific study for a better understanding of the link between friction-induced vibrations and squeal noise via acoustic measurements is not deeply conducted. The use of microphone array in far-field to investigate links between friction-induced vibration and squeal noise will be one of the contribution of the proposed study.

The proposed experimental study is carried out from the bench Friction-Induced Vibration and noiseE at Ecole Centrale de Lyon (FIVE@ECL). This experimental bench has been developed by the authors since 2015 to characterize brake squeal from the self-excited vibrations of a disc brake assembly and the generated acoustic noise in near- or far-field [31]. A complete analysis of the stationary squeal event has already been proposed in [31] and the reproducibility of both squeal frequency content and radiated acoustic profiles in far field for a given set of operational parameters and for a specific brake system have been demonstrated in the case of stationary squeal events. In the present study the major contribution aims at proposing an extension of these previous results [31] by demonstrating the repeatability of squeal events also from a transient point of view.

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The paper is organized as follows: firstly, a brief description of the experimental bench FIVE@ECL, as well as the main characteristic of brake squeal coming from the previous study performed by the authors [31] are given. Secondly, a deep analysis of the repeatability of the squeal time signature from experimental tests performed on the bench FIVE@ECL is discussed. This subject will be treated by investigations on both friction-induced vibration and squeal noise. Finally, the potential links between friction-induced vibrations and squeal noise for transient and stationary squeal events will be highlighted.

2. Description of the experimental bench FIVE@ECL

This section is devoted to the description of the experimental bench FIVE@ECL and the main characteristics of the phenomena of friction-induced vibration and squeal noise during a typical braking test. First of all the brake system under study is briefly presented as well as the instrumentation implemented on the test bench FIVE@ECL for data acquisition. Then a reminder of the main characteristics of the non-linear signature of squeal phenomena for the brake system under study is proposed. A more detailed description of the test bench FIVE@ECL as well as the squeal analysis can be found in [31].

2.1. Overview

A picture of the test bench FIVE@ECL is given in Figure 1. It consists of:

- the brake system under study that is composed of a disc, a pair of pads and a caliper;
- an electric motor for rotating the brake disc and being able to overcome the maximum braking torque;
- an inertial flywheel to store some rotational kinetic energy equivalent to the translational kinetic energy of a real-world brake system;
- a manual hydraulic pump for applying the brake pressure;
- two independent rigid supports for the rotating and no-rotating parts of the brake system, as well as a specific support for the electric motor;
- an anechoic cage for a fine and unperturbed characterization of squeal noise;
- and instrumentation and data acquisition hardware for vibration and acoustic measurements and analysis.

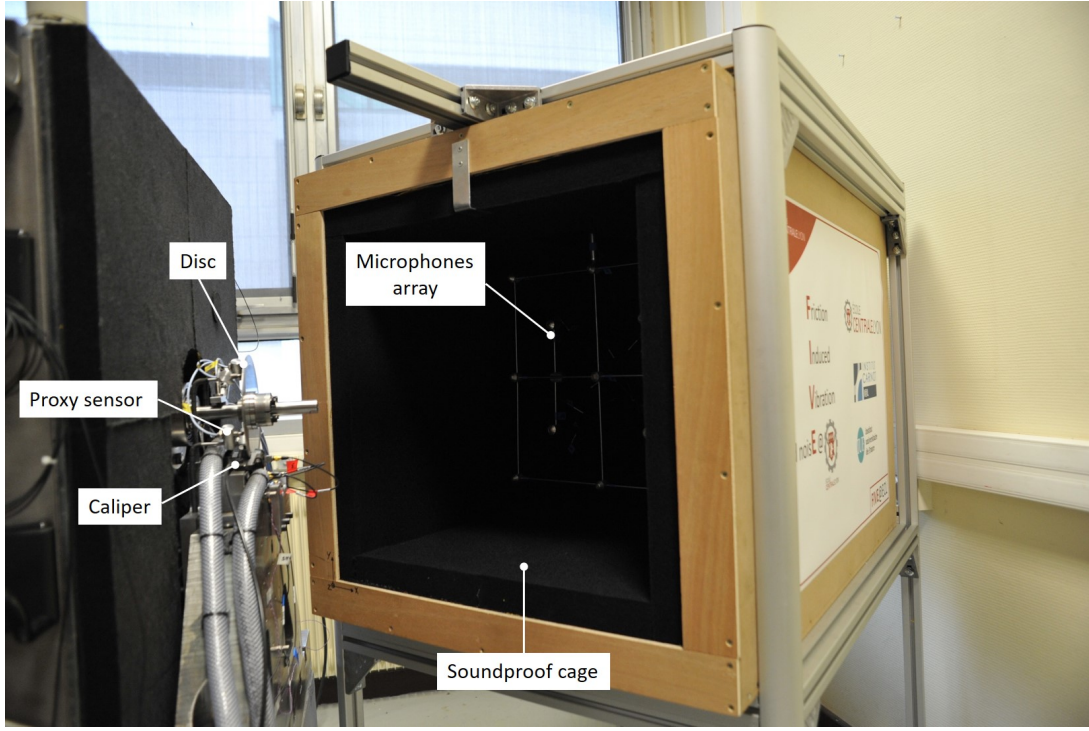
2.2. Instrumentation and data acquisition

The experimental measurement devices of the test bench FIVE@ECL have been implemented to allow a complete characterization of squeal phenomena by analyzing both friction-induced vibration and radiated noise. More precisely, the instrumentation implemented on the test bench is composed of:

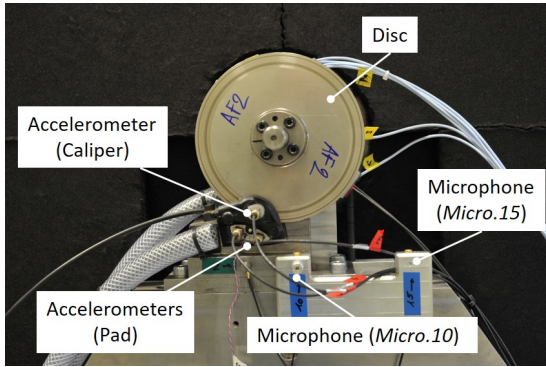
- four miniature triaxial accelerometers (*TriAxe.1* to *TriAxe.4*), two for each pad;
- one miniature triaxial accelerometer (*TriAxe.5*) placed on the brake caliper;
- four proximitor sensors (*Proxy.1* to *Proxy.4*) to perform non-contact measurement of the rotating disc displacement in the transverse direction;
- two microphones (*Micro.10* and *Micro.15*) placed in the vicinity of the brake system in order to perform acoustic measurements in near-field;
- one array composed of thirteen microphones (*Micro.1* to *Micro.14* except *Micro.10*) and placed in front of the brake system in order to perform far-field measurements in the direction normal to the brake system. It should be noted that this microphones array is located inside an anechoic cage which provides high-level acoustic absorption and thus drastically reduces unwanted reflected waves. In the following, *Micro.FF* will denotes averaged data over all far-field microphones.

These experimental devices of the bench FIVE@ECL can be partially seen on Figure 1. The channel identification and position of each sensor is given in [31]. In addition to these sensors, the pressure applied to the pads, the rotating speed of the disc, the motor torque and the temperature close to the pad/disc brake system are measured during each experimental test. The pressure and the rotating speed of the disc are two controllable parameters, whereas the motor torque and the temperature are uncontrolled parameters directly resulting from the braking test conditions.

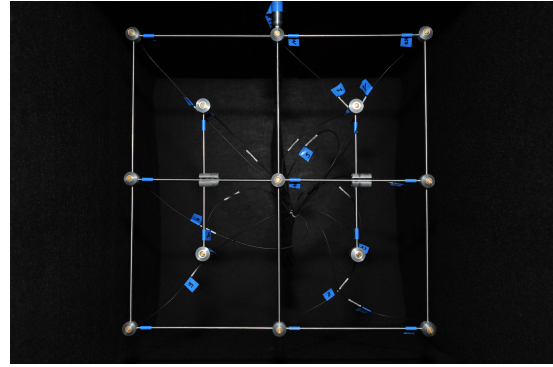
Finally a data acquisition platform CompactDAQ from National Instrument is used to perform the dynamic signal acquisition. The sampling rate of each channel of the data acquisition system is 25600 S/s with a 24-bit resolution.



(a)



(b)



(c)

Figure 1: Experimental bench FIVE@ECL (a) overview (b) brake system under study (c) microphones array

2.3. Experimental protocol and squeal phenomena main characteristics

The experimental protocol and the complete squeal analysis have been fully described in [31]. Here the objective is to give the reader the necessary information for the understanding of the study proposed later in this paper.

The duration of an experimental test is in most cases 20 s and can be decomposed in three phases:

- $0 < t < 3$ s: in this first phase, the rotational speed is constant and equal to its nominal value, no pressure being applied to the brake system;
- $3 < t < 7$ s: this second phase corresponds to the transient braking response during which the hydraulic pressure is progressively applied up to its nominal value;
- $t > 7$ s: in this final phase, both the hydraulic pressure and the rotation speed are stable and remain equal to their nominal values.

Figure 2(a) give the typical evolution of the four operational parameters (i.e. the rotating speed of the disc, the motor torque, the brake pressure and the pad temperature) during a braking test. All the raw data of this specific braking test, named Case 1, are available as open-data [32] and correspond to nominal values of 200 rpm for the rotation speed and 9.2 bars for the brake pressure.

Considering more specifically the squeal analysis during a braking test, the squeal characteristics based on vibration and acoustic measurements can be performed during the second and third phases. During the second phase, the two pads and the disc come into contact which induces the appearance and increase of friction-induced vibrations and squeal noise. A stabilization of the squeal phenomena is obtained during the last phase. In [31], it has been shown that the frequencies that characterize the squeal signature in the last phase are quite similar for both the vibration and acoustic measurements. The repeatability of both the squeal frequency content and the radiated acoustic profiles

in far field has been validated too. Nevertheless differences in vibratory and acoustic levels were highlighted. Based on this previous results, the global nonlinear vibratory signature of brake squeal for the system under study is composed of:

- three fundamental frequencies $f_1=580$ Hz, $f_2=770$ Hz and $f_3=2040$ Hz;
- fourteen harmonic components of the first fundamental frequency nf_1 for $n = 2, \dots, 15$;
- and a frequency at 870 Hz that could be a potential harmonic combination of the first and third fundamental frequencies since $-2f_1 + f_3=870$ Hz.

For more details on the complete and detailed analysis of squeal phenomena, the reader may refer to [31]. These basic results should be kept in mind as they will be used as reference in the rest of the present paper.

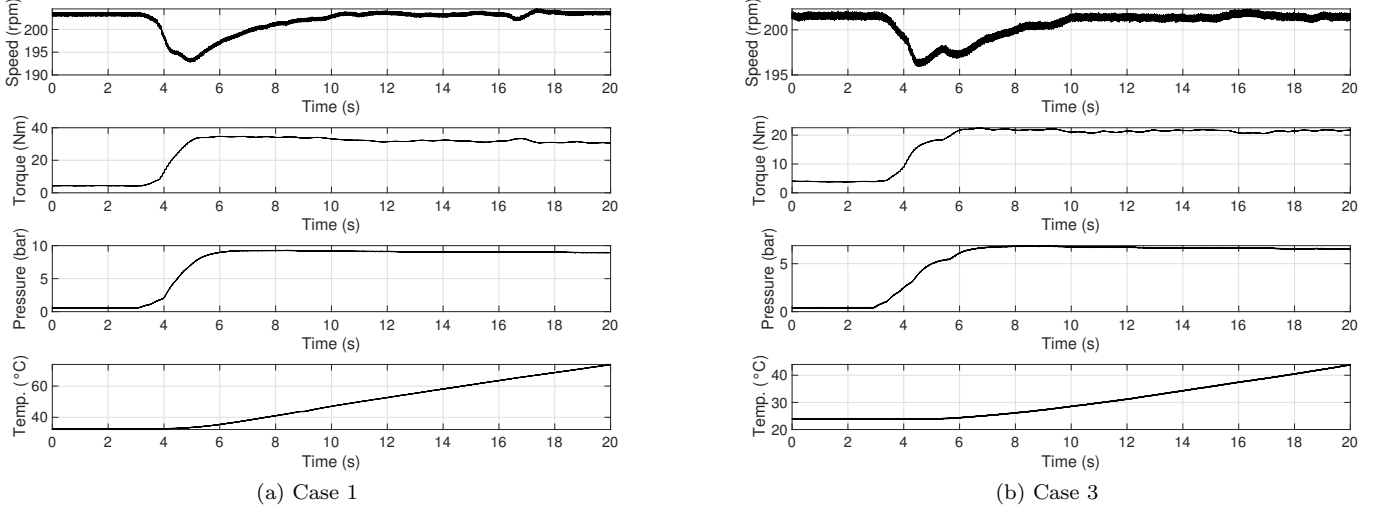


Figure 2: Typical operational parameters during a braking test on the FIVE@ECL experimental bench

3. Repeatability of the transient squeal time signature

3.1. Motivations of the proposed study

The global reproducibility and repeatability of the squeal events have been previously demonstrated in [31] by restricting the squeal analysis on the nonlinear signature when the phenomena of friction-induced vibrations is well stabilized, i.e. in the third phase previously described in section 2.3. It was also concluded that the repeatability of vibratory levels was less convincing, even if the global trends are respected for both acoustic and vibratory levels.

Thereby one of the major open issues is to investigate the repeatability of the squeal events with respect to the evolution of the nonlinear signatures of brake squeal not only during the stabilization of friction-induced vibrations, but also during its generation and its potential variation in time. This will be the subject of the Section 3.3 and in order to carry out such an analysis, the frequency content of the nonlinear friction-induced vibration and the associated squeal noise will be analyzed and compared for two data sets:

- obtained with the same operational conditions;
- but with two different brake systems of the same design;
- and thus separated by some disassembly-reassembly operations.

The two data sets retained correspond to Case 1 and Case 3 already analyzed in [31]. This choice is consistent with the fact that these two tests have very similar operational conditions and also that a complete analysis has already been carried out on these two braking tests concerning the vibration and acoustic signal of the squeal event during their stabilized phase. Thus the reader will be able to refer to all these preliminary results without having to present them again here. Table 1 summarizes the characteristics of the two selected cases and Figures 2 provides the associated evolutions of the four operational parameters. Table 2 gives the global nonlinear vibratory and acoustic signature of brake squeal retained for the proposed study but only the twelve most significant frequency contributions were retained and this is the reason why, by comparison with the study previously done in [31], the low-level frequency contribution at 870 Hz is not considered here. For the reader comprehension, the frequency value indicated in Table 2 for each contribution corresponds to the frequency for which the maximum acoustic level has been observed over the entire braking test.

Reference case	Pressure (bar)	Rotational speed (rpm)	Phase 1 (s)	Phase 2 (s)	Phase 3 (s)
Case 1	9.2	203	[0.0 ; 3.1]	[3.1 ; 6.7]	[6.7 ; 20.0]
Case 3	7.7	203	[0.0 ; 3.0]	[3.0 ; 7.5]	[7.5 ; 20.0]

Table 1: Main characteristics of the two cases under study

Frequency signature	Case 1 (Hz)	Case 3 (Hz)
f_1	584	579
f_2	769	759
$2f_1$	1169	1164
$3f_1$	1754	1754
f_3	2019	2024
$4f_1$	2334	2334
$5f_1$	2924	2919
$6f_1$	3509	3499
$7f_1$	4094	4084
$8f_1$	4679	4664
$9f_1$	5264	5254
$10f_1$	5849	5834

Table 2: Nonlinear vibratory and acoustic signature of brake squeal for the two cases under study

In order to carry out the proposed study, it is also necessary to define some similarity indicators between the two selected data sets. Some prospective studies have been conducted by the authors on this subject; they are not presented and discussed here in detail for the sake of brevity. It appeared that a classic analysis and comparison of the raw temporal data of brake squeal does not allow to quantify the repeatability of the time evolution of the squeal signature. The main origin of such conclusion is based on the fact that the time shift of the appearance of the squeal phenomenon between two different braking tests and the continuous fluctuations of friction-induced vibrations and squeal noise makes it impossible to use basic criteria. Thus, a specific approach for the analysis and comparison of the two selected cases have been developed to provide a simple but robust and complete answer to the squeal events time repeatability. The explanation of the criteria selected for this study is the subject of the following Section 3.2.

3.2. Methodology and comparison criteria developed for the study

In order to compare and classify the squeal events both from a point of view of friction-induced vibrations and squeal noise, it was chosen to analyze the temporal event of the squeal by characterizing in a simplified way each temporal evolution of the frequencies present in the non-linear signature of the squeal. Each frequency evolution in time will be characterized by its increase, decrease and/or stabilization during a braking test. The nomenclature used to describe the evolution of the frequency contribution of friction-induced vibrations or squeal noise is as follows:

- **s** denotes a stable contribution;
- **d** denotes a decreasing contribution;
- **i** denotes an increasing contribution;
- **id** denotes an increasing contribution, followed by a decreasing contribution;
- **di** denotes a decreasing contribution, followed by an increasing contribution;
- **n** indicates that the selected frequency is not present or significant for the considered sensor;
- and - indicates that the selected frequency is not retained in the similarity analysis. This choice results from the fact that it is not possible to have a relevant and reliable judgment on the evolution of the contribution during all the braking test due to its possibly noisy low-level amplitude.

All the frequency contribution for all sensors will be characterized from these six potential temporal evolution representations of a frequency signature. At first glance this approach may appear really basic, but it appears that these six possibilities make it possible to characterize in a global way all the evolutions observed on each sensor.

Similarly the intensity of the frequency contribution for both the vibration amplitude and acoustic noise is characterized by considering a three possibilities nomenclature:

- **H** denotes a high level frequency contribution;
- **M** denotes a medium level frequency contribution;
- and **L** denotes a low level frequency contribution.

Intensity	Accelerometer (dB)	Proxymitor (dB)	Microphone NF (dB)	Microphone FF (dB)
L	$[-15; -5]$	$[5; 20]$	$[-40; -20]$	$[35; 45]$
M	$[-5; 5]$	$[20; 30]$	$[-20; -5]$	$[45; 65]$
H	$[5; 15]$	$[30; 45]$	$[-5; 5]$	$[65; 75]$

Table 3: High, medium and low intensity ranges for each type of sensors

	Case 1					
	s	d	i	di	id	n
Case 3	s	1	0.6	0.6	0.4	0
	d	0.6	1	0.2	0.4	0
	i	0.6	0.2	1	0.4	0
	di	0.4	0.4	0.4	1	0.2
	id	0.4	0.4	0.4	0.2	1
	n	0	0	0	0	1

Table 4: Criterion value α_{ij} to determine the similarity between two signals in regards to their evolutions in time

Obviously if a given frequency evolution is characterized by **n**, the symbol chosen to characterize its level would be **L**. Table 3 gives typical range values used to assess this amplitude evaluation for all kind of sensors implemented on the FIVE@ECL bench.

Given this preliminary analysis, two consistency criteria between the i^{th} frequency contribution for the j^{th} specific sensor and for the two considered cases, may be evaluated:

- The first one concerns the evolutions in time of the considered frequency contribution for the two cases. Table 4 defines values that have been chosen to characterize the similarity of evolution of friction-induced vibrations or squeal noise in regards to the nomenclature previously defined. If the frequency evolutions in time are identical, the criterion will have a value of 1. If the frequency evolutions in time are very different, the criterion value is set to 0. If the frequency evolutions in time has some similarity while being somewhat different, the criterion value is set to 0.2 or 0.4. This criterion value is denoted α_{ij} .
- The second one concerns the intensity of the considered frequency contribution and Table 5 defines values that have been chosen. If the intensity levels are identical, the criterion value is 1. If the intensity level is high for one case while in the other case it is low, the criterion value is 0.2. In all others cases, the criterion value is 0.7. This criterion value is denoted β_{ij} .

It is then possible to evaluate the correlation between the i^{th} frequency contribution for the j^{th} specific sensor and for the two considered cases by calculating the correlation indicator $C_{ij} = \alpha_{ij}\beta_{ij}$. Finally the global correlation for the j^{th} sensor and for all detected frequencies in the frequency range of interest \bar{C}_j is evaluated as the mean of C_{ij} :

$$\bar{C}_j = \frac{1}{N_f} \sum_{i=1}^{N_f} C_{ij} \quad (1)$$

where N_f is the number of detected frequencies in the frequency range of interest. If a frequency has been characterized by the symbol - for Case 1 or Case 3, the number of detected frequencies is of course counted down by one unit for the considered sensor. It should be noted that if the similarity indicator \bar{C}_j is close to 1, it means that there is a nearly perfect correlation between the Case 1 and the Case 3 for the considered sensor. In the following, it is admitted that values above 0.7 indicate that the two cases are well correlated, and therefore that the repeatability of transient squeal events is demonstrated. Values below 0.5 will be considered as an indication of non-repeatability of the squeal events, whereas values between 0.5 and 0.7 should be considered with much caution: they may or may not indicate correlation between the two selected cases and the considered sensor.

In the same way, the global correlation factor for the i^{th} frequency contribution \hat{C}_i is introduced as the mean over all sensors of C_{ij} :

$$\hat{C}_i = \frac{1}{N_s} \sum_{j=1}^{N_s} C_{ij} \quad (2)$$

		Case 1		
		H	M	L
Case 3	H	1	0.7	0.2
	M	0.7	1	0.7
	L	0.2	0.7	1

Table 5: Criterion value β_{ij} to determine the similarity between two signals in regards to their intensity levels

where N_s is the number of available sensors for the correlation analysis. Obviously, above remarks concerning typical values of \hat{C}_j still holds for \hat{C}_i .

3.3. Main results

Before assessing the repeatability of squeal events in time based on the previously exposed methodology, a brief overview of results for some selected measurements are provided below. Figures 3, 4, 5 and 6 show the evolution of the far-field noise emissions during the braking test for the two cases under study. Figure 7 shows the spectrogram from the squeal noise in the near-field and Figure 8 gives some typical examples of spectrograms obtained from friction-induced vibration on the pads, the caliper and the disc.

Comparing vibration and acoustic measurements from Case 1 and Case 3 on Figures 3, 4, 5, 6, 7 and 8, it can be observed without any ambiguity that the nonlinear vibratory signature of brake squeal as well as the general repeatability in time of the squeal events is really good. For example, if the repeatability of the radiated acoustic profiles in far field is examined, it can be more particularly seen that on both cases:

- the acoustic pattern is different for each frequency but repeatable for Cases 1 and 3;
- the acoustic levels at $3f_1$, $4f_1$, $5f_1$ and $8f_1$ are significantly higher than the others throughout the duration of the squeal events;
- the acoustic levels at $2f_1$ and f_3 are significantly lower than the others throughout the duration of the squeal events;
- the acoustic levels at f_2 slowly increases throughout the braking test;
- the acoustic levels at the first fundamental frequency f_1 is high at the beginning of the braking tests and then decrease to stay at low levels until the end of the braking test;
- the acoustic levels at $4f_1$ stays at high levels over a large part of the braking test and then decrease to low levels at the end of the test.

In order to confirm these observations, the repeatability of the squeal events for transient and stationary states, i.e. the second and third phases of the experimental protocol, has been analyzed on all measurements using the previously presented methodology. Spectrograms of each sensor for Cases 1 and 3 are calculated and the similarity between the two cases for both the evolutions and the associated intensity of frequency contributions are estimated.

Time evolution, intensity of frequency contributions and correlation indicators C_{ij} of squeal events are given for some specific sensors in Tables 6 and 7. Table 8 summarizes the correlation factor \hat{C}_j for all sensors. It should be noted that a large part of the sensors present a high correlation factor: 21 out of 22 have values greater than 0.8 and 12 out of 22 have values greater than 0.9 which means that the similarity is almost perfect. Only the sensor *Triaxe.2.X* has a correlation factor below 0.8.

Table 9 summarizes the correlation factors \hat{C}_i for all significant frequencies in the selected frequency range. It clearly appears that the repeatability of squeal events in time is excellent and unambiguous for all frequencies with a correlation factor superior to 0.8, except for the frequency f_1 for which the correlation factor is equal to 0.48. Nevertheless, this non-perfect repeatability for the frequency contribution f_1 has to be put into perspective since this contribution does not correspond to one of the most important contributions during the squeal phenomenon. Moreover, without considering the slight level increase at the end of the test for Case 1 particularly in far-field acoustic measurement, global evolution of this frequency contribution for the two cases looks quite similar. This specific observation is still an open issue concerning the repeatability for the frequency contribution f_1 but the authors would like to point out two remarks on it. Firstly, there is a difference on one physical operational condition between the two cases at the end of the test : for Case 1, pads temperature reaches 70°C whereas it reaches only 42°C for Case 3. Secondly, as it can be guessed on Figures 8(e) and (f), a frequency decrease contribution exists in both case in the frequency range 700-900 Hz and this frequency decrease seems to get closer to the first fundamental frequency f_1 in Case 1 than in Case 3. As temperature increase induces in most case structural softening, the combination of these two remarks leads the authors to assume that some characteristics of the time squeal signature may be linked to the temperature evolution via the frequency shift of some structural modes. In other words, if the braking test Case 3 had lasted longer, maybe an increase of the frequency contribution f_1 would have been observed thus inducing a better correlation between the two cases for this frequency contribution f_1 . This increase of the frequency contribution f_1 would be the consequence of a complementary energy contribution coming from the decrease of the frequency around 700-900 Hz. Of course this is only a hypothesis based on some observations on very low-level frequency contributions. Therefore further investigations will be done in the future to explain this phenomenon in details. However this analysis confirm without any doubt the excellent repeatability of the squeal events in time for both friction-induced vibrations and squeal noise, as it is proved by the excellent correlation factor \hat{C}_i for the highest level frequency contributions at $3f_1$, $4f_1$, $5f_1$ and $8f_1$.

	Frequency	Evolution		Level		C_{ij}
		Case 1	Case 3	Case 1	Case 3	
<i>Micro.10 (NF)</i>	f_1	di	d	H	H	0.40
	f_2	-	-	L	L	-
	$2f_1$	s	s	H	H	1.00
	$3f_1$	s	s	H	H	1.00
	f_3	-	-	L	L	-
	$4f_1$	id	id	H	H	1.00
	$5f_1$	s	s	H	H	1.00
	$6f_1$	s	s	H	H	1.00
	$7f_1$	s	s	H	H	1.00
	$8f_1$	s	s	H	H	1.00
	$9f_1$	s	s	M	M	1.00
	$10f_1$	s	s	H	H	1.00
						$\bar{C}_{25} = 0.94$
<i>Micro.15 (NF)</i>	f_1	s	s	H	H	1.00
	f_2	s	s	M	M	1.00
	$2f_1$	s	s	H	H	1.00
	$3f_1$	s	s	H	H	1.00
	f_3	s	s	M	M	1.00
	$4f_1$	d	d	H	H	1.00
	$5f_1$	s	s	H	H	1.00
	$6f_1$	d	d	M	H	0.70
	$7f_1$	d	d	H	H	1.00
	$8f_1$	d	d	H	H	1.00
	$9f_1$	s	s	M	L	0.70
	$10f_1$	s	s	H	H	1.00
						$\bar{C}_{30} = 0.95$
<i>Microphone array (FF)</i>	f_1	di	d	H	H	0.40
	f_2	i	i	L	L	1.00
	$2f_1$	s	s	M	M	1.00
	$3f_1$	s	s	H	H	1.00
	f_3	s	s	L	L	1.00
	$4f_1$	id	id	H	H	1.00
	$5f_1$	d	d	H	H	1.00
	$6f_1$	s	d	M	M	0.60
	$7f_1$	d	d	M	M	1.00
	$8f_1$	d	d	H	H	1.00
	$9f_1$	s	s	M	M	1.00
	$10f_1$	d	d	M	H	0.70
						$\bar{C}_{FF} = 0.89$

Table 6: Time evolution, intensity of frequency contributions and correlation indicators C_{ij} and \bar{C}_j of squeal events for FF and NF microphones

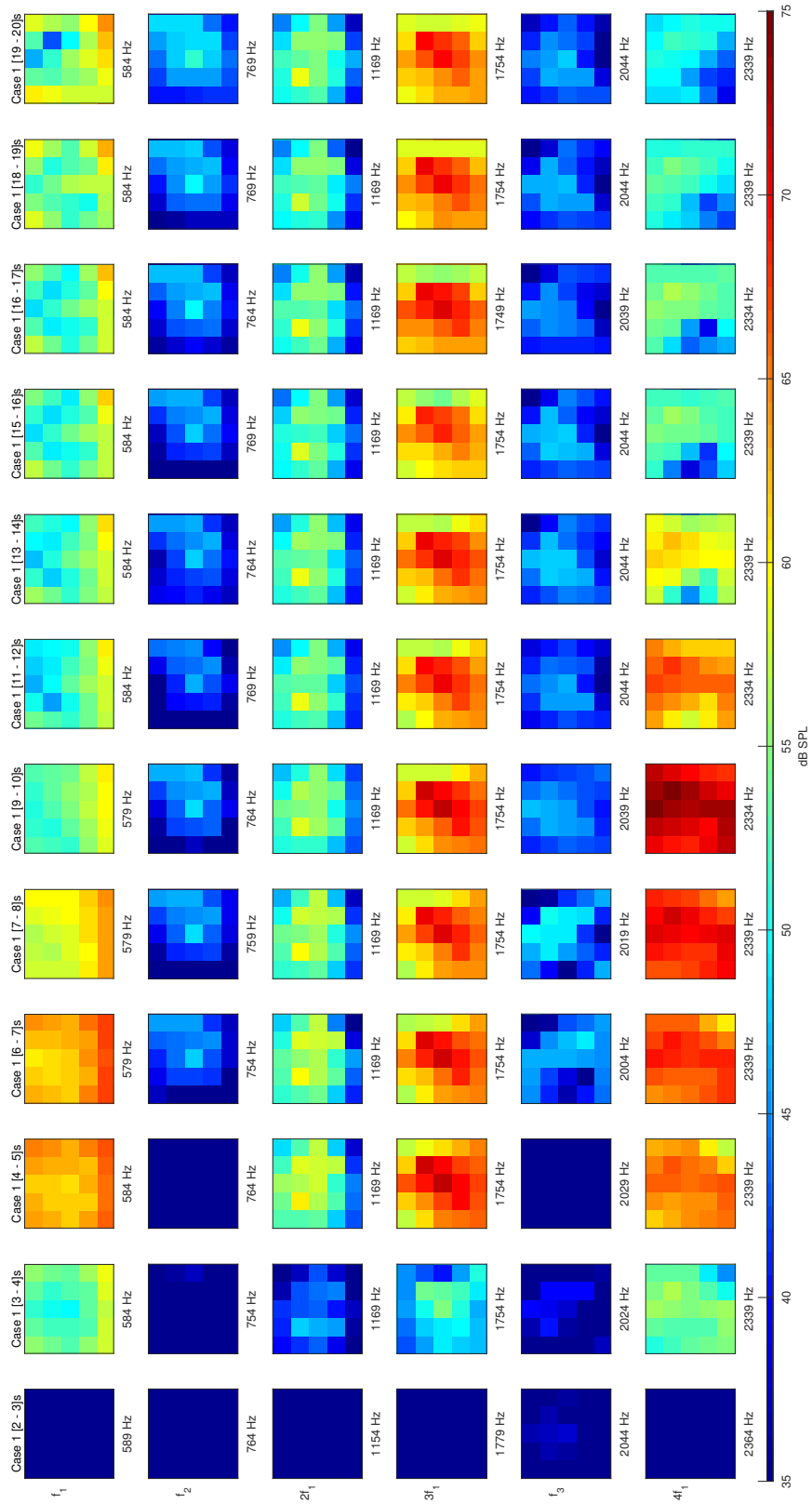


Figure 3: Evolution of the radiated acoustic profiles in far-field for Case 1 and for frequency band [500;2500]Hz

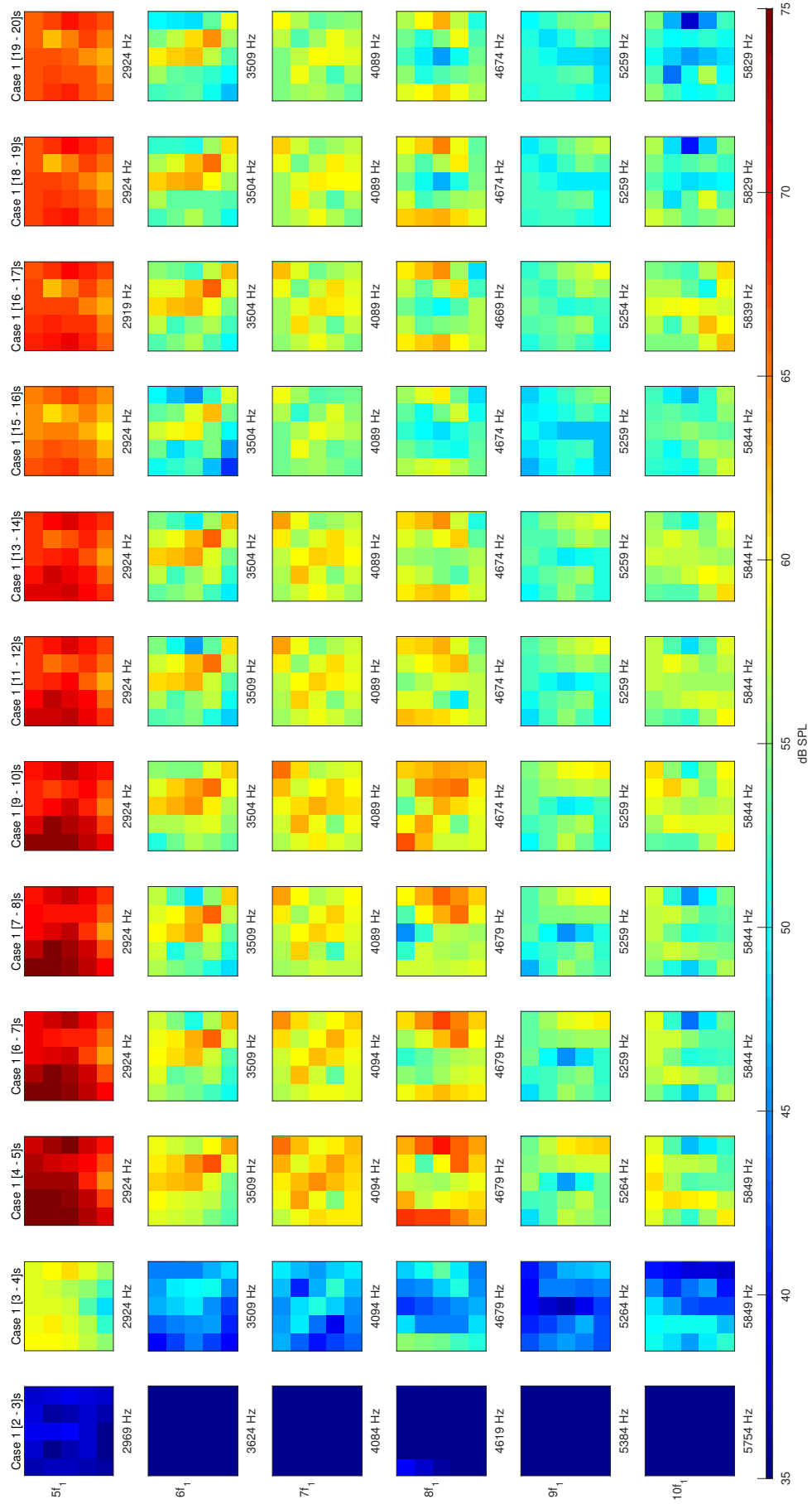


Figure 4: Evolution of the radiated acoustic profiles in far-field for Case 1 and for frequency band [2500;6100]Hz

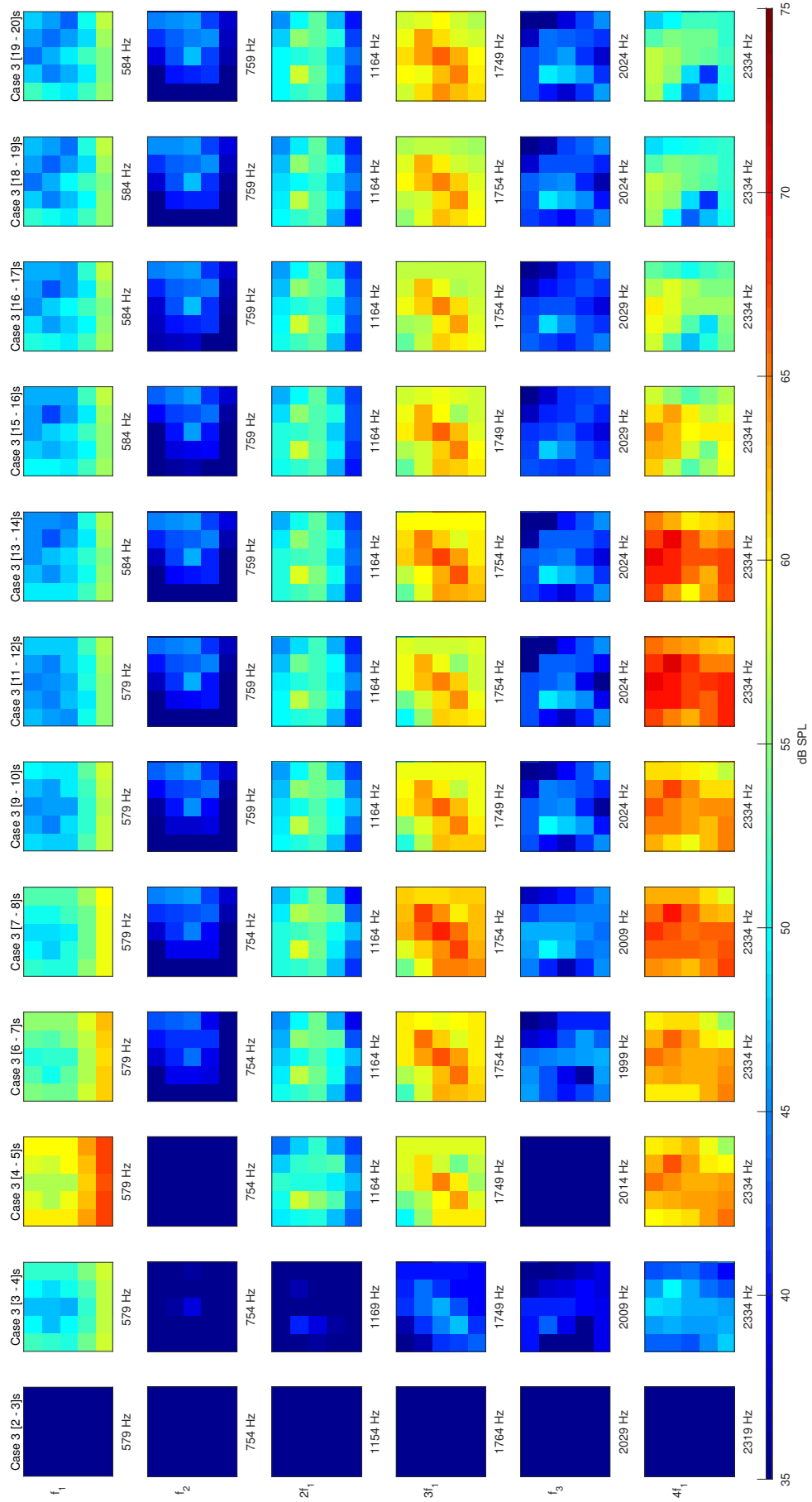


Figure 5: Evolution of the radiated acoustic profiles in far-field for Case 3 and for frequency band [500;2500]Hz

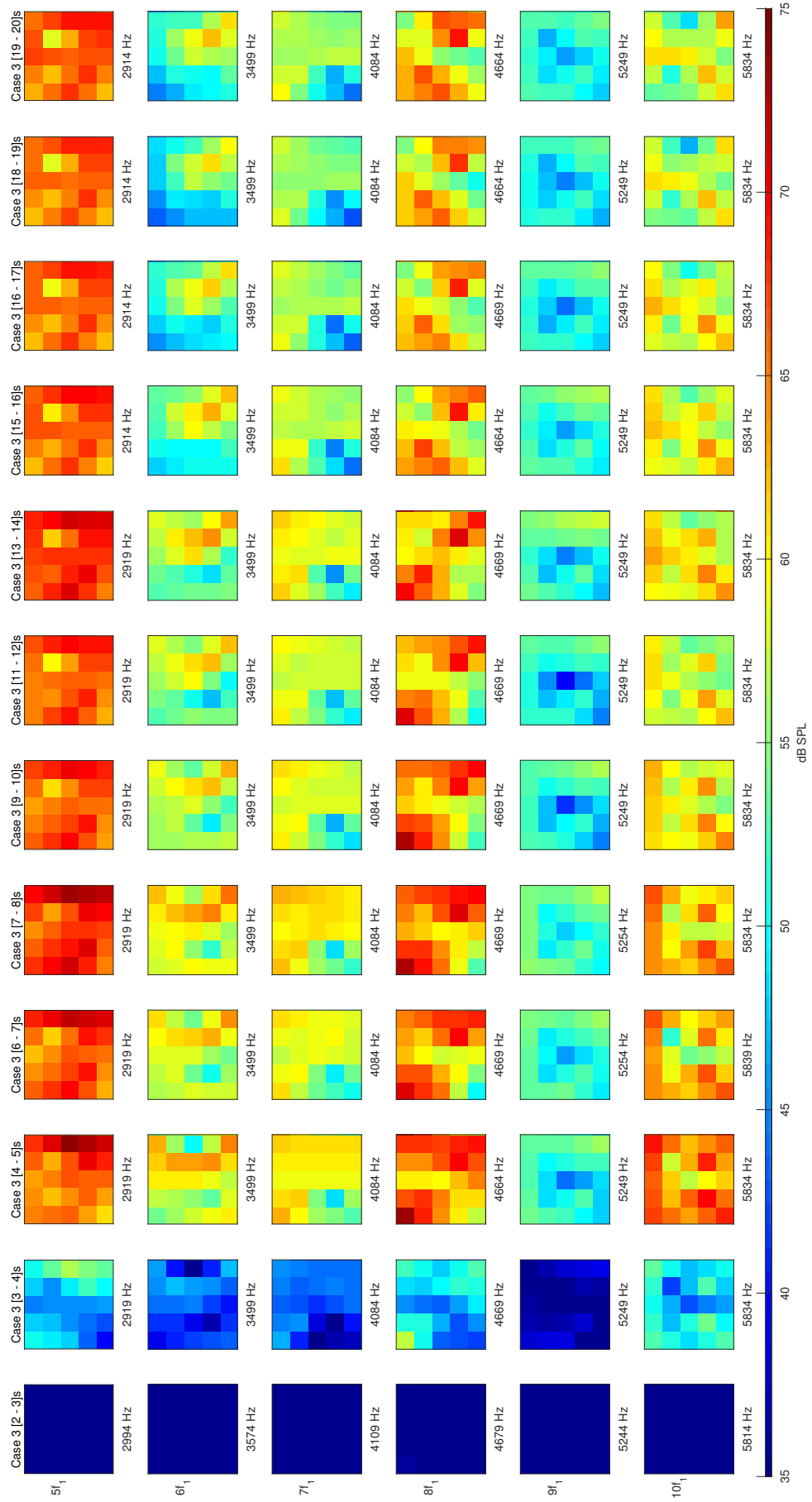


Figure 6: Evolution of the radiated acoustic profiles in far-field for Case 3 and for frequency band [2500;6100]Hz

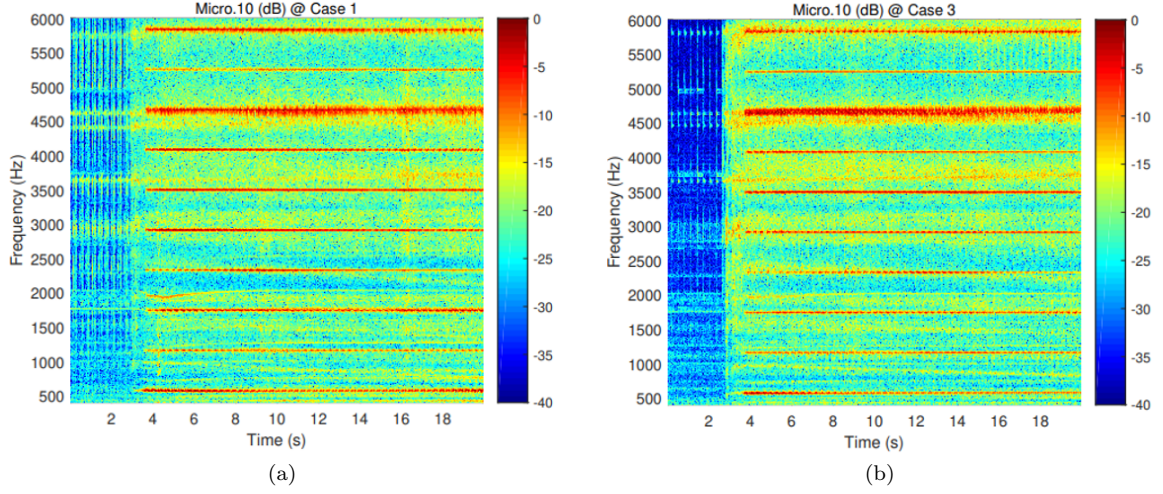


Figure 7: Spectrograms of near-field squeal noise at *Micro.10* (a) Case 1 (b) Case 3

	Frequency	Evolution		Level		C_{ij}
		Case 1	Case 3	Case 1	Case 3	
<i>TriAxe.1.Y</i> (Pad)	f_1	di	s	M	L	0.28
	f_2	n	n	L	L	1.00
	$2f_1$	d	d	H	M	0.70
	$3f_1$	s	s	H	H	1.00
	f_3	n	n	L	L	1.00
	$4f_1$	s	d	H	H	0.60
	$5f_1$	s	s	H	H	1.00
	$6f_1$	s	s	H	H	1.00
	$7f_1$	s	s	H	H	1.00
	$8f_1$	s	s	H	H	1.00
	$9f_1$	s	s	H	H	1.00
	$10f_1$	s	s	H	H	1.00
						$\bar{C}_2 = 0.88$
<i>TriAxe.5.X</i> (Caliper)	f_1	di	d	M	M	0.40
	f_2	n	n	L	L	1.00
	$2f_1$	d	d	H	H	1.00
	$3f_1$	s	s	H	H	1.00
	f_3	n	n	L	L	1.00
	$4f_1$	d	d	H	H	1.00
	$5f_1$	s	s	H	H	1.00
	$6f_1$	s	s	H	H	1.00
	$7f_1$	s	d	M	H	0.42
	$8f_1$	s	s	H	H	1.00
	$9f_1$	s	s	H	H	1.00
	$10f_1$	s	s	H	H	1.00
						$\bar{C}_{13} = 0.90$
<i>Proxy.4</i> (Disc)	f_1	di	d	H	H	0.40
	f_2	n	n	L	L	1.00
	$2f_1$	id	id	H	H	1.00
	$3f_1$	i	i	H	H	1.00
	f_3	n	n	L	L	1.00
	$4f_1$	s	s	L	L	1.00
	$5f_1$	d	d	H	H	1.00
	$6f_1$	-	d	M	M	-
	$7f_1$	d	d	M	M	1.00
	$8f_1$	d	id	M	H	0.28
	$9f_1$	d	s	L	L	0.60
	$10f_1$	-	-	L	L	-
						$\bar{C}_{34} = 0.83$

Table 7: Time evolution, intensity of frequency contributions and correlation indicators C_{ij} and \bar{C}_j of squeal events for *TriAxe.1.Y*, *TriAxe.5.X* and *Proxy.4* sensors

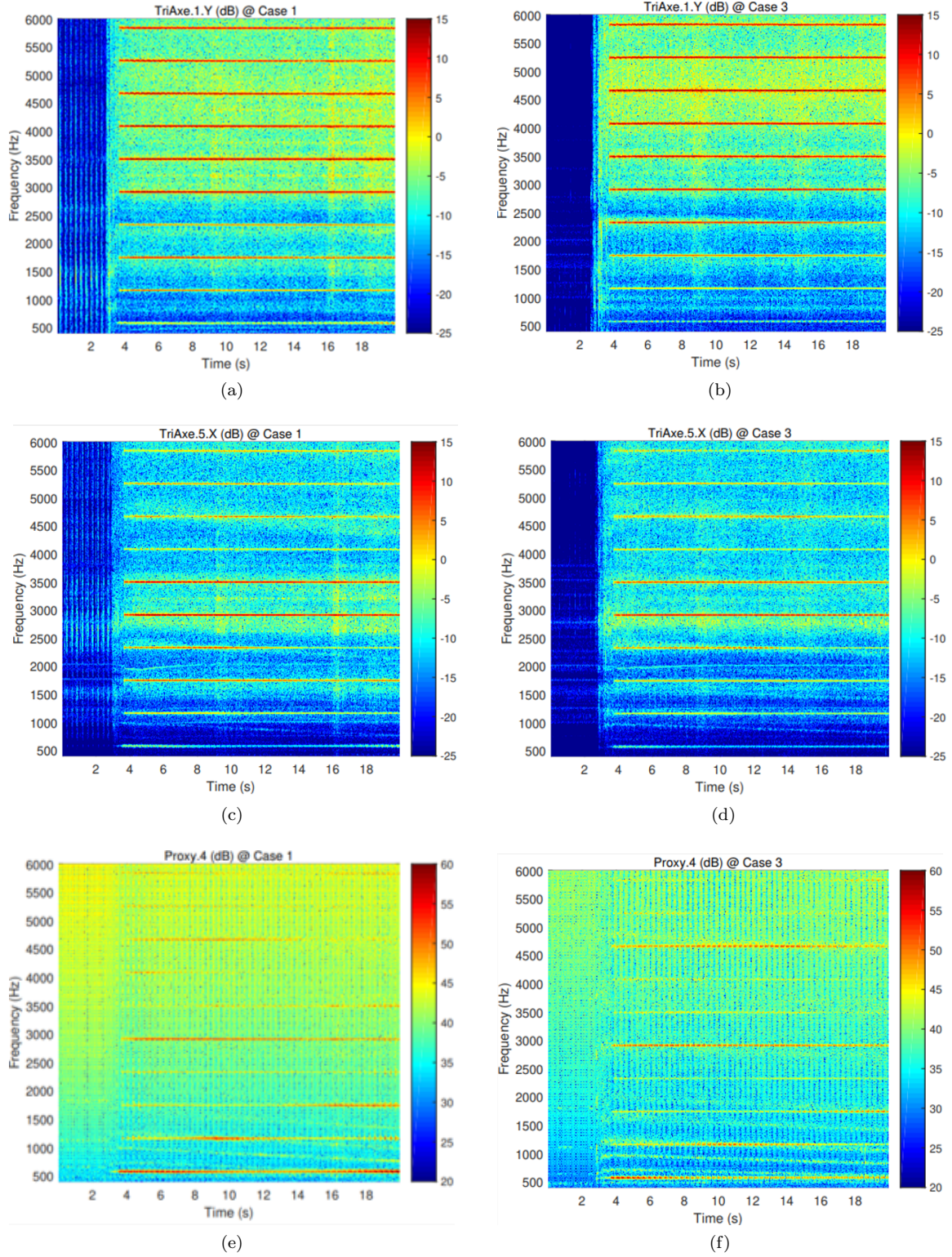


Figure 8: Spectrograms of friction-induced vibrations at (a,b) *TriAxe.1.Y* (c,d) *TriAxe.5.X* and (e,f) *Proxy.4* (a,c,e) Case 1 (b,d,f) Case 3

Sensor	\bar{C}_j
<i>TriAxe.1.X</i>	0.83
<i>TriAxe.1.Y</i>	0.88
<i>TriAxe.1.Z</i>	0.94
<i>TriAxe.2.X</i>	0.78
<i>TriAxe.2.Y</i>	0.84
<i>TriAxe.2.Z</i>	0.93
<i>TriAxe.3.X</i>	0.81
<i>TriAxe.3.Y</i>	0.95
<i>TriAxe.3.Z</i>	0.93
<i>TriAxe.4.X</i>	0.89
<i>TriAxe.4.Y</i>	1.00
<i>TriAxe.4.Z</i>	0.94
<i>TriAxe.5.X</i>	0.90
<i>TriAxe.5.Y</i>	0.98
<i>TriAxe.5.Z</i>	0.90
<i>Micro.10</i>	0.94
<i>Micro.15</i>	0.95
<i>Microphone array</i>	0.89
<i>Proxy.1</i>	0.86
<i>Proxy.2</i>	0.93
<i>Proxy.3</i>	0.93
<i>Proxy.4</i>	0.83

Table 8: Correlation indicators \bar{C}_j of squeal events for each sensor

Frequency	f_1	f_2	$2f_1$	$3f_1$	f_3	$4f_1$	$5f_1$	$6f_1$	$7f_1$	$8f_1$	$9f_1$	$10f_1$
\hat{C}_i	0.45	1	0.87	0.96	0.95	0.94	0.99	0.89	0.91	0.88	0.86	0.92

Table 9: Correlation indicators \hat{C}_i of squeal events for each frequency

4. Links between acoustic and vibration squeal events in time

The objective of this last section is to undertake the potential links between acoustic and vibration squeal events in time. In order to achieve such an objective, the acoustic measurements in near-field for each microphone, as well as the acoustic measurements in far-field are compared with the vibration measurements coming from accelerometers and proximitors by analyzing the similarities of evolutions of their frequency contributions.

Results are summarized in Figure 9 and Figure 10. For the reader comprehension, the first column corresponds to the acoustic measurement selected to perform the correlation analysis between squeal noise and friction-induced vibrations. All other columns correspond to measurements on accelerometers and proximitors. The letter code indicated in each cell corresponds to the evolution of each frequency contribution for each sensor, as previously defined in Section 3.3. Then each case of the acoustic measurement is colored according to the signature evolution in time of the concerned frequency contribution (i.e. one color for one specific evolution in time). If this evolution of the frequency contribution is also observed on one accelerometer or one proximitor, the corresponding cell of the vibration measurement is colored in the same way. In other words, coloring a box of the table for vibration measurements indicates a possible link with the squeal noise regarding the evolution of the frequency contribution. Finally if the letter associated with the acoustic measurement is indicated in purple, it means that there is no direct identified link between squeal noise and friction-induced vibrations.

By analyzing all results presented in Figure 9 and Figure 10, some general observations may be brought:

- The links between acoustic and vibration measurements is essentially the same for Case 1 and Case 3 which is again consistent with the efficiency of the test bench FIVE@ECL for repeatability of squeal events.
- For the two most important squeal noise frequency contributions at $4f_1$ and $5f_1$, the link between acoustic and vibration measurements is identical for the two cases. The increase and decrease evolution of the frequency contribution at $4f_1$ is detected for both the microphone in far field and one microphone in near field (i.e. *Micro.10*), as well as the vibration measurements on the disc. Similarly decreasing of the frequency contribution at $5f_1$ is detected on the microphone in far field and on the vibration measurements on the disc.
- All the stable frequency contributions for noise in far-field and near-field can be associated with stable contributions detected on the vibration measurements of pads and caliper.

- The increase and/or decrease evolution of squeal noise in far field for a specific frequency can generally be linked with the evolution of the vibration signature of the disc, except for the frequency f_1 for which the link between squeal noise and friction-induced vibrations concerns both the disc, the caliper and the two pads for Case 1 and the disc and the caliper for Case 3.
- Differences appear on the evolution of the frequencies signature between acoustic responses in near fields and far field. For example the friction noise detected by the NF microphone *Micro.10* is more directly related to the evolution of the vibration contributions from the two pads and caliper, while the squeal noise in far-field brings out links with the vibration contributions of both the disc and the pad. This experimental observation may be in agreement with the fact that the microphone *Micro.10* in near-field is located in the vicinity of the pads and the caliper, while the microphone array in far-field is more able to capture the acoustic noise radiated by the different components of the brake system. As a result, conclusions on the link between friction noise in near field and friction-induced vibration are not exactly the same than those between squeal noise in far field and friction-induced vibration. It can also be noted that links between the nonlinear vibration and the radiated acoustic profiles for the two microphones in near field (i.e. *Micro.10* and *Micro.15*) are not exactly similar. This fact is directly related to the position of each microphone in near field: *Micro.10* is situated near the pads and caliper whereas *Micro.15* is situated on right side of the brake system (see Figure 1).
- Two frequencies identified in squeal noise are not apparently detected in the vibration signatures, f_2 and f_3 . First of all it is recalled that these two contributions correspond to low acoustic levels detected in far field, as shown in Figures 3 and 4. Concerning more specifically the frequency contribution f_2 , its emergence can be detected on the proximitor sensors (see Figures 8). It corresponds more exactly to the frequency contribution which is characterized by a pronounced decrease in frequency. This frequency decrease is repeatable for different braking tests. This phenomenon appears to be in connection with the temperature rise of the brake system, as previously explained in Section 3.3. More investigations have to be performed in the future to bring further conclusions on this point. Concerning more specifically the low level frequency contribution f_3 in far-field, it could be due to a small vibration coming from the rigid support which would explain why this contribution is not found on the various elements of the brake system. This observation and the validity of this hypothesis will be the subject of more particular attention in future studies.

Finally it can be concluded that there is no obvious link between the acoustic levels and the vibration levels for each frequency contribution. The most important frequency contributions of squeal noise in near-field and far-field are not necessarily the most important frequency contributions of friction-induced vibrations detected on the two pads, the disc and the caliper. This classical result is consistent with the fact that some vibration modes radiate more than others and that the intensity of squeal noise is dependent on the position of microphones. These results also demonstrate the interest of performing measurements of squeal noise and not only friction-induced vibrations for a better investigation of squeal phenomena.

5. Conclusion

The present study investigates friction-induced vibrations and squeal noise by using experimental data coming from braking tests performed on the benchmark Friction-Induced Vibration and noise at École Centrale de Lyon (FIVE@ECL).

More specifically the reproductibility and repeatability of the transient squeal phenomenon has been investigated by developing a methodology for comparing the evolution of the nonlinear frequencies signatures of brake squeal not only during the stabilization of friction-induced vibrations, but also during its generation and its potential variation in time.

This study demonstrates that the vibration and acoustic phenomena during squeal events are repeatable on the bench FIVE@ECL which allows to use this experimental bench to perform an complete analysis on the links between the transient friction-induced vibrations and squeal noise in far-field and near-field.

Specific analysis has also been undertaken in order to experimentally point out the potential links between the emergence of friction-induced vibrations and the squeal noise in near-field and far-field. It has been demonstrated that it is possible to give information on the contributions of the different elements of the brake system (i.e. the disc, the two pads or the caliper) on frequencies signature of the acoustic noise during transient and stationary squeal events.

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10f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	i	-	-	-
9f ₁	s	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	-	-	d
8f ₁	d	s	s	s	d	s	s	s	s	s	s	s	s	s	s	id	d	d	-	d
7f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	d	d	d
6f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	-	-	-	-
5f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	d	d	d
4f ₁	id	s	s	s	s	s	s	s	s	s	s	s	s	d	s	s	id	id	id	s
f ₃	s	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
3f ₁	s	s	s	s	s	s	s	s	s	s	d	s	s	s	s	s	i	i	i	i
2f ₁	s	d	s	s	s	d	d	s	s	id	s	s	s	d	s	s	d	id	id	id
f ₂	i	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
f ₁	di	i	di	di	i	di	di	i	i	s	di	s	di	di	s	s	di	di	di	di
	Micro.FF	TriAxe.1.X	TriAxe.1.Y	TriAxe.1.Z	TriAxe.2.X	TriAxe.2.Y	TriAxe.2.Z	TriAxe.3.X	TriAxe.3.Y	TriAxe.3.Z	TriAxe.4.X	TriAxe.4.Y	TriAxe.4.Z	TriAxe.5.X	TriAxe.5.Y	TriAxe.5.Z	Proxy.1	Proxy.2	Proxy.3	Proxy.4

10f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	i	-	-	-
9f ₁	s	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	-	-	d
8f ₁	s	s	s	s	d	s	s	s	s	s	s	s	s	s	s	id	d	d	-	d
7f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	d	d	d
6f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	-	-	-	-
5f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	d	d	d
4f ₁	id	s	s	s	s	s	s	s	s	s	s	s	s	d	s	s	id	id	id	s
f ₃	-	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
3f ₁	s	s	s	s	s	s	s	s	s	s	d	s	s	s	s	s	i	i	i	i
2f ₁	s	d	s	s	s	d	d	s	s	id	s	s	s	d	s	s	d	id	id	id
f ₂	-	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
f ₁	di	i	di	di	i	di	di	i	i	s	di	s	di	di	s	s	di	di	di	di
	Micro.10	TriAxe.1.X	TriAxe.1.Y	TriAxe.1.Z	TriAxe.2.X	TriAxe.2.Y	TriAxe.2.Z	TriAxe.3.X	TriAxe.3.Y	TriAxe.3.Z	TriAxe.4.X	TriAxe.4.Y	TriAxe.4.Z	TriAxe.5.X	TriAxe.5.Y	TriAxe.5.Z	Proxy.1	Proxy.2	Proxy.3	Proxy.4

10f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	i	-	-	-
9f ₁	s	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	-	-	d
8f ₁	d	s	s	s	d	s	s	s	s	s	s	s	s	s	s	id	d	d	-	d
7f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	d	d	d
6f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	-	-	-	-
5f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	d	d	d
4f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	d	s	s	id	id	id	s
f ₃	s	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
3f ₁	s	s	s	s	s	s	s	s	s	s	d	s	s	s	s	s	i	i	i	i
2f ₁	s	d	s	s	s	d	d	s	s	id	s	s	s	d	s	s	d	id	id	id
f ₂	s	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
f ₁	s	i	di	di	i	di	di	i	i	s	di	s	di	di	s	s	di	di	di	di
	Micro.15	TriAxe.1.X	TriAxe.1.Y	TriAxe.1.Z	TriAxe.2.X	TriAxe.2.Y	TriAxe.2.Z	TriAxe.3.X	TriAxe.3.Y	TriAxe.3.Z	TriAxe.4.X	TriAxe.4.Y	TriAxe.4.Z	TriAxe.5.X	TriAxe.5.Y	TriAxe.5.Z	Proxy.1	Proxy.2	Proxy.3	Proxy.4

Figure 9: Overview of possible links between squeal noise and friction-induced vibration for Case 1

10f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	i	-
9f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	-	s
8f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	d	id
7f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	-	d	d
6f ₁	d	s	s	s	d	s	s	s	s	s	s	s	s	s	s	s	-	d	d
5f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	d	d
4f ₁	id	s	d	s	s	d	s	s	s	s	s	s	s	d	s	s	id	id	id
f ₃	s	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
3f ₁	s	s	s	s	s	d	s	s	s	s	s	s	s	s	s	s	i	i	i
2f ₁	s	d	s	s	s	s	s	s	s	s	s	s	s	d	s	s	d	id	id
f ₂	i	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	d	s	s	d	d	d
Micro.FF TriAxe.1.X TriAxe.1.Y TriAxe.1.Z TriAxe.2.X TriAxe.2.Y TriAxe.2.Z TriAxe.3.X TriAxe.3.Y TriAxe.3.Z TriAxe.4.X TriAxe.4.Y TriAxe.4.Z TriAxe.5.X TriAxe.5.Y TriAxe.5.Z Proxy.1 Proxy.2 Proxy.3 Proxy.4																			

10f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	i
9f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	-	-
8f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	d	id
7f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	-	d	d
6f ₁	s	s	s	s	d	s	s	s	s	s	s	s	s	s	s	s	-	d	d
5f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	d	d
4f ₁	id	s	d	s	s	d	s	s	s	s	s	s	d	s	s	s	id	id	id
f ₃	-	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
3f ₁	s	s	s	s	s	d	s	s	s	s	s	s	s	s	s	s	i	i	i
2f ₁	s	d	s	s	s	s	s	s	s	s	s	s	d	s	s	s	d	id	id
f ₂	-	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	d	s	s	d	d	d
Micro.10 TriAxe.1.X TriAxe.1.Y TriAxe.1.Z TriAxe.2.X TriAxe.2.Y TriAxe.2.Z TriAxe.3.X TriAxe.3.Y TriAxe.3.Z TriAxe.4.X TriAxe.4.Y TriAxe.4.Z TriAxe.5.X TriAxe.5.Y TriAxe.5.Z Proxy.1 Proxy.2 Proxy.3 Proxy.4																			

10f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	i
9f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	-	-
8f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	d	id
7f ₁	d	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	-	d	d
6f ₁	d	s	s	s	d	s	s	s	s	s	s	s	s	s	s	s	-	d	d
5f ₁	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	d	d	d
4f ₁	d	s	d	s	s	d	s	s	s	s	s	s	d	s	s	s	id	id	id
f ₃	s	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
3f ₁	s	s	s	s	s	d	s	s	s	s	s	s	s	s	s	s	i	i	i
2f ₁	s	d	s	s	s	s	s	s	s	s	s	s	d	s	s	s	d	id	id
f ₂	s	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n	n
f ₁	s	s	s	s	s	s	s	s	s	s	s	s	d	s	s	s	d	d	d
Micro.15 TriAxe.1.X TriAxe.1.Y TriAxe.1.Z TriAxe.2.X TriAxe.2.Y TriAxe.2.Z TriAxe.3.X TriAxe.3.Y TriAxe.3.Z TriAxe.4.X TriAxe.4.Y TriAxe.4.Z TriAxe.5.X TriAxe.5.Y TriAxe.5.Z Proxy.1 Proxy.2 Proxy.3 Proxy.4																			

Figure 10: Overview of possible links between squeal noise and friction-induced vibration for Case 3