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Automotive friction-induced noises

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Friction-induced noises are numerous in the automotive field. They also involve a large number of structures. Wiper squeal, seat squeak or dashboard creak are some examples of these noises. The different names traditionally used to describe these noises allow a first classification, especially based on their acoustical signature.

From an experimental side, an exploratory test-rig has been designed. This can generate friction-induced noises with simple structures and automotive materials. Qualitative sensitivity studies have demonstrated the test-rig ability to produce squealing, squeaking and creaking noises.

From a numerical side, a phenomenological model has been investigated. This model brings together the main physical concepts (stick-slip, sprag-slip, mode-coupling) explaining the origin of friction-induced noises. Time simulations enable to qualitatively obtain the vibrational behaviour at the origin of the squealing, squeaking and creaking noises as well as the information about the contact states occurring for each of these categories.

Finally, an algorithm for an automatic classification of vibrational behaviours has also been developed. Noise charts based on this algorithm are presented and highlight sets of parameters leading to non-noisy areas, particularly sought when designing an automotive system for instance.

1 Introduction

Still these days, friction is a phenomenon which is not well-known and overcome yet. Its complexity partly lies in the fact that it can have many consequences [1] such as wear, energy dissipation, structure deformation, vibration or noise. Moreover, its consequences are extremely sensitive to the even slight variation of environmental and design parameters, adding challenges to its understanding. Friction-induced vibrations and noises do not demean this observation. In the automotive field, these noises are annoying and perceived by the customer as a lack of quality [2]. Therefore it is necessary for automotive manufacturers to anticipate a potential risk of noise occurrence on the vehicle systems. From this perspective, understanding the physical origin of friction-induced noises is essential. This explains the large amount of studies about brake squeal for instance [3, 4]. In this paper, a database of automotive friction-induced noises is presented. A classification of these noises is proposed. Then, a test-rig is presented as well as a phenomenological model. A classification algorithm based on the contact states is also proposed. Finally, noise charts using this algorithm illustrate the sensitivity of friction-induced noises towards the model design parameters.

2 Friction-induced noises classification

2.1 Automotive friction-induced noises

A database of automotive friction-induced noises has been established. This non-exhaustive database highlights the diversity of automotive systems affected by this issue. Brakes, wipers, sunroofs, seats, dashboards or latches are some examples of these systems. Most of the noises from the database have been obtained while operating the systems, sometimes manually. Currently, the database contains about forty friction-induced noises recorded on about twenty different systems.

Particular denominations are often assigned to friction-induced noises. One can for instance talk about squealing, squeaking or creaking noises. The noises from the database can be classified according to these denominations. Moreover, the qualitative analysis of the noises time history enables a primary recognition of their category.

In the upper part of Figure 4, three automotive systems have been chosen to illustrate this assumption. Time histories of a squealing noise from a sunroof, a squeaking noise from a door hinge and a creaking noise from a latch are presented. Squeal can be associated to a tonal sound, often in high fre-

quency. Although the noise level varies over the duration of the noise, these variations are not abrupt. By performing a time-frequency analysis of this signal, it appears that the frequency content is constant throughout the squeal. Squeaking noises are generally lower in frequency than squealing noises. Time histories are also much more jerky and the variations can be abrupt compared to squealing noises. Time-frequency analysis shows also that the frequency content is not as constant as could be the one of a squealing noise. Creaking noise is an impulsional noise repeated quite periodically. When two structures are in contact, the impulsional feature is actually due to the release of energy occurring when passing from a sticking phase to a slipping phase.

2.2 Test-rig noises

An exploratory test-rig has been designed. This can generate friction-induced noises with simple structures and automotive materials. This test-rig, presented in Figure 1, puts into contact a one-side bounded plate and a rubber joint. This rubber joint is a 2cm-long piece of an inner waist seal. In order to obtain noise with relative ease, the joint is put into contact on the non-flocked side, which is usually not in contact with the glass. The preload can be varied thanks to a tray that can support weights and a sinusoidal velocity is imposed on the rubbing system thanks to a shaker.

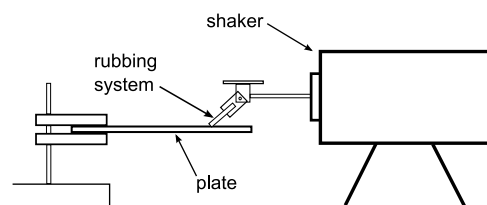


Figure 1: Test-rig reproducing friction-induced noises

Qualitative sensitivity studies to preload, velocity, temperature or hygrometry have been performed. These enables to highlight various acoustical and vibrational signatures. The characteristic time evolution of squealing, squeaking and creaking noises, previously observed for the automotive friction-induced noises from the database, are reproduced by the test-rig as it can be seen in the middle part of Figure 4.

It should be noted that the vast majority of tested configurations produced squealing or squeaking noises. The creaking noise is very difficult to reproduce on this test-rig. It seems to appear when preload is high enough to mainly observe no relative motion between the two structures in con-

tact (sticking phase). This will be discussed and numerically shown later in this paper. However, the test-rig is not enable to ensure such a preload. Using other material like steel rather than rubber could also make easier the reproduction of creaking noise.

2.3 Numerical friction-induced vibrations

Concepts like stick-slip [5], sprag-slip [6] or mode-coupling instabilities [7, 8] are often mentionned in the litterature as being the mechanisms at the origin of friction-induced noises. However, these concepts are independently studied, whereas nothing prevents them to cohabit in a real system. With that in mind, the minimalist model that can handle these three concepts has been investigated. Thus, this phenomenological model contains the necessary physics for explanation of a wide variety of friction-induced noises. In this paper, time simulations applied on this model will be shown.

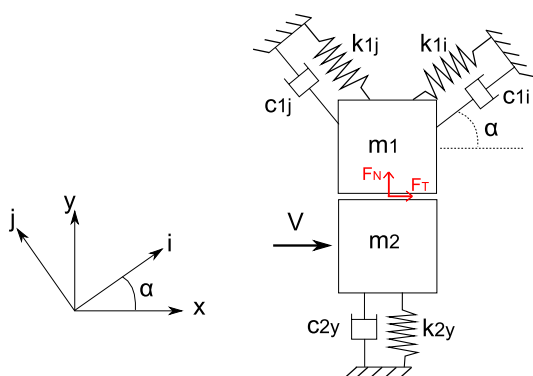


Figure 2: Phenomenological model

The investigated system is a three degrees-of-freedom model, presented in Figure 2. It can be seen as representing the contact between a rubber joint m_1 and a plate m_2 with the stiffnesses k_{1i} and k_{1j} being respectively the traction-compression stiffness and flexion stiffness of the rubber joint, and the stiffness k_{2y} being the bending stiffness of the plate. An initial preload F is provided by the system stiffnesses. A velocity V is imposed at the mass 2 in the x direction, generating a displacement of mass 1 by friction. Losses are also introduced by the intermediary of dashpots c_{1i} , c_{1j} and c_{2y} . Finally, the incidence angle α of the rubber joint on the plate is defined as the angle between the x and i axes.

The vibrational behaviour of the model is investigated by performing time simulations so adapted numerical methods are required. For time integration, a β_2 explicit scheme of Newmark is used and detailed in [9]. A method based on kinematics is used for the contact management and described in [10]. This method considers three possible contact states: slip, stick and separation.

There are several friction laws existing in the litterature, some of them are reminded in [11]. For this work, Coulomb friction law is used to relate normal and tangential contact forces F_N and F_T . As shown in Figure 3, the kinetic friction coefficient μ_d is independent of the sliding velocity V_{rel} and lower than the static friction coefficient μ_s .

According to the sets of parameters used for the simulations, three kinds of vibrational behaviour can be distinguished for the mass 1, each of them are represented in the lower part of Figure 4. Vibrational behaviours from numerical simulations, sound pressures radiated from measurements

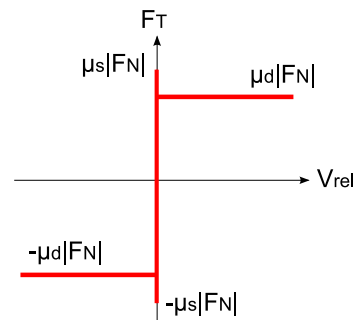


Figure 3: Friction law with a kinetic friction coefficient independent of the sliding velocity and lower than the static friction coefficient

on test-rig and automotive noises can be qualitatively compared. It appears that the phenomenological model permits to reproduce the vibrational behaviours and understand the mechanisms at the origin of squealing, squeaking and creaking noises.

3 Classification algorithm

3.1 Time simulations

Time simulations are performed using a contact management method based on kinematics. Thus, three contact states may occur between masses 1 and 2: slip, stick and separation. For each of these states, the contact forces are derived differently. The kinematics and the friction law used allows to know which contact state occurs at each time step. In Figure 5 is shown a classical result of a time simulation performed on the phenomenological model. Velocity imposed at mass 2 is sinusoidal in order to get closer to the excitation imposed by the shaker from the test-rig. The excitation frequency chosen for illustration is 5Hz. A simulation of 1s is performed, so five roundtrips of mass 1 on mass 2 are observed. It appears on the acceleration curves that each going phase gives rise to a vibrational instability, characterized by a response that diverges, then stabilizes and attenuates. This response is characteristic of the vibrational behaviour causing a squealing noise. The coming phase does not show such a response. In this phase, the system is stable, so no noise is radiated. Below, the contact states at each time step are shown. One can observe that the going phases do not lead to the same contact states that the coming phases. Indeed, during the going phases, there are slip, adhesion and separation, whereas during the coming phase, only slip is observed. By zooming into the going phase, it is possible to see in more details the alternation of these different contact states. For example, one can note a larger proportion of separation than slip for this configuration.

Depending on the configurations, the slip, stick or separation phase may occur and last more or less time. By imposing a constant velocity profile to the mass 2, it is interesting to study the proportions of each phase when the response becomes periodic or quasi-periodic. Thus, the slip, stick and separation rates are defined. These rates represent in percentage the ratio between the duration of a contact state and the duration of the time window analysed. The Figure 6 shows these three rates for a wide range of preload and velocity configurations. For example, we observe that when preload is

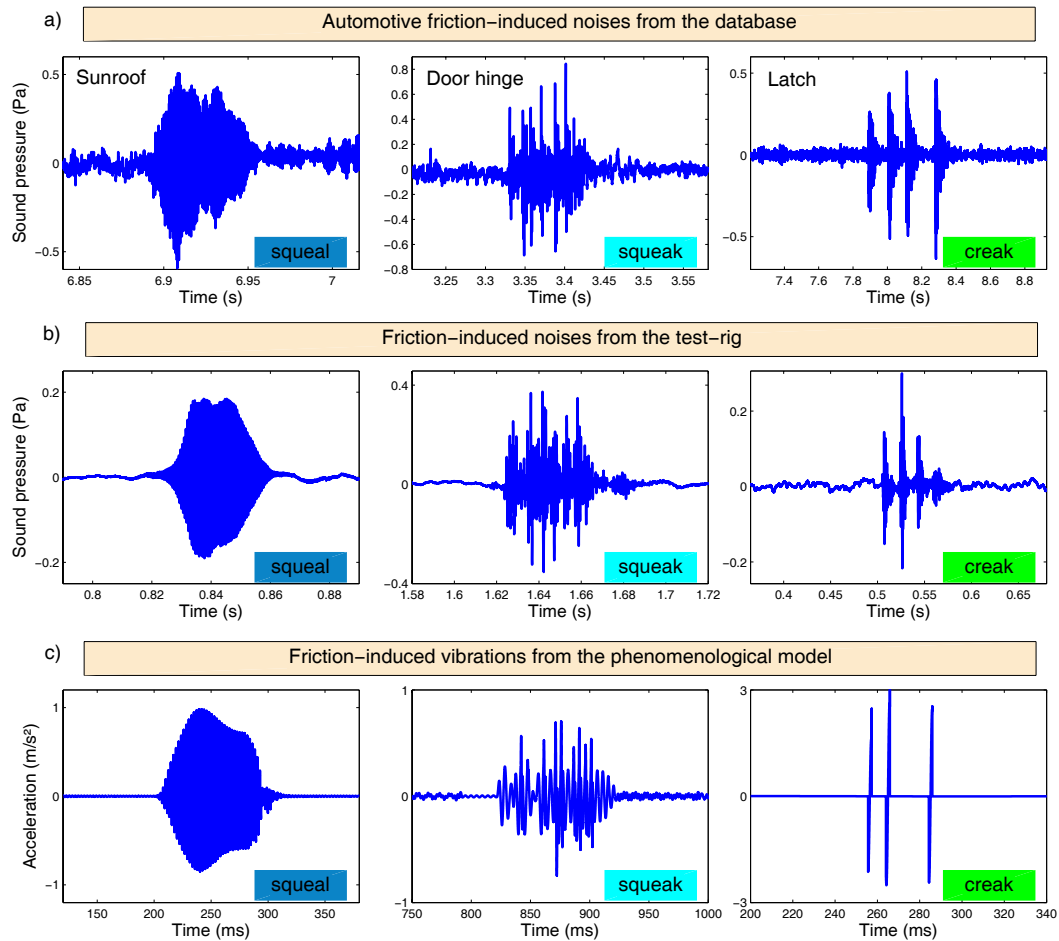


Figure 4: a) Classification of automotive friction-induced noises. b) Qualitative reproduction of squealing, squeaking and creaking noises with the test-rig. c) Qualitative reproduction of the vibrational behaviours at the origin of squealing, squeaking and creaking noises with the phenomenological model.

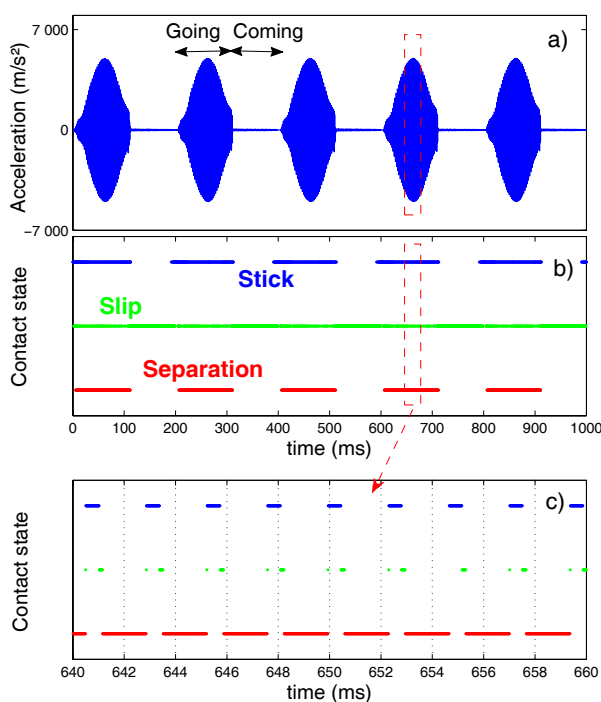


Figure 5: Typical time response from the phenomenological model - Case of a squealing configuration

important and imposed velocity is low, the predominant contact state is adhesion. The two illustrations represent two different angles of incidence (70° and 150°) and show remarkable dissimilarities. Thus, the extreme sensitivity of the vibrational behaviour of this rubbing system towards preload, imposed velocity and incidence angle is highlighted by this representation of contact states.

3.2 Contact state for each category

For each noise category, informations about the evolution of contact states is given thanks to numerical simulations. Therefore, an algorithm for automatic classification of vibrational behaviours can be proposed. This is based on the analysis of the proportion and the time evolution of the contact states. This is illustrated in Figure 7, where one can see the contact states for four typical configurations, described in Table 1. These configurations represent the vibrational behaviour corresponding to squealing, squeaking and creaking noises. A vibrational behaviour generating no noise is also illustrated.

For non-noisy configurations, only a slip state is involved in the response. Indeed, no contact non-linearity occurs as no instability (stick-slip, sprag-slip or mode-coupling) is reached. The time evolution of the vibrational behaviour would show a very low amplitude as well as an attenuation of the response with time. For creaking noise, stick is the predominant state.

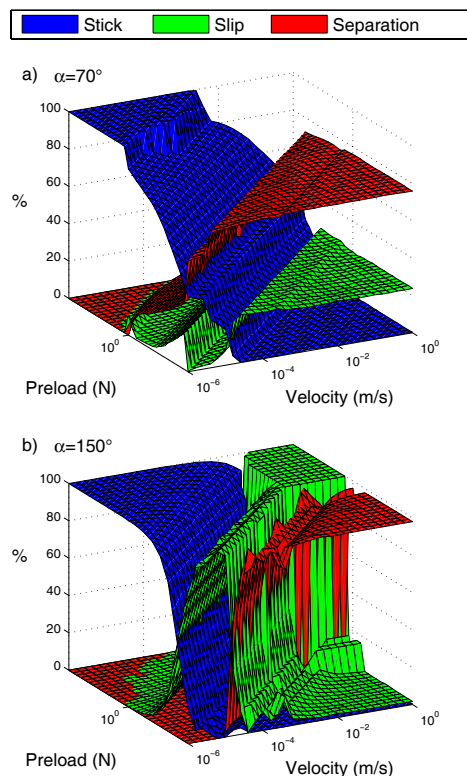


Figure 6: Evolution of slip, stick and separation rates with preload and imposed velocity

Indeed, the noise is generated only when moving from a stick state to a slip state. One can note that slip phases are significantly shorter than stick phases. For squealing noise, alternation of contact states is regular. This can effectively explain the constant spectral content of a such noise. For squeaking noise, alternation of contact states is not as regular as for squeal noise. This reflects the jerky feature of this noise.

Thus, the algorithm takes into account these informations about contact states in order to automatically categorize a vibrational behaviour. However this algorithm uses threshold values that can be questioned because established by subjective analysis. Nevertheless, it enables to distinguish some trends towards design parameters as shown next.

4 Biparametrical noise charts

In Figure 8 are presented two biparametrical noises charts. The left one corresponds to a going phase and the right one to a coming phase of the mass 1 on the mass 2. Several preload and friction coefficient configurations are simulated. The algorithm previously discussed indicates the noise category for each of these configurations. Thus, for low friction coefficients and not too great preloads, no noise is radiated in going phase as well as in coming phase. By increasing the friction coefficient, mode-coupling instabilities occur in going phase, causing squealing noise. One can observe that no noise is radiated in coming phase. The simulation previously described in Figure 5 is a typical example of such a response. For greater values of preload, the radiated noise is closer to squeaking noise. One can note that creaking noise is obtained only for very high preloads, whether in going or coming phase. Of course, both charts were obtained for a

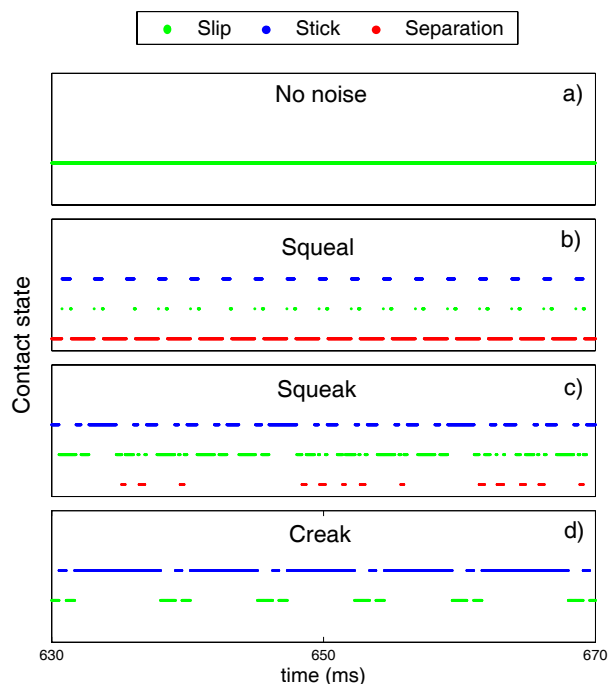


Figure 7: Evolution of contact states with time for a) no noise, b) squeal, c) squeak and d) creak categories

Table 1: Sets of parameters used for time simulations shown in Figure 7

Category	No noise	Squeal	Squeak	Creak
α	70	70	70	70
μ_d	0.2	0.6	0.2	0.2
μ_s	0.8	0.8	0.8	0.8
m_1	0.1	0.1	0.1	0.1
m_2	0.4	0.4	0.4	0.4
k_{1i}	$1e7$	$1e7$	$1e7$	$1e7$
k_{1j}	$1e6$	$1e6$	$1e6$	$1e6$
k_{2y}	$1e6$	$1e6$	$1e6$	$1e6$
c_{1i}	1	1	1	1
c_{1j}	1	1	1	1
c_{2y}	1	1	1	1
F	20	20	200	2000
A_{exc}	$4e-3$	$4e-3$	$4e-3$	$4e-3$
f_{exc}	5	5	5	5

particular set of parameters and can not be generalized to every sets of parameters. However, these charts allow a visualization of which parameters have an influence on the noise occurrence but also on the transition from one category to another. Some fields of investigation require a special knowledge of these transitions. This is particularly true for musical acoustics, when a violinist is paying attention to keep playing in the squeal area and not to cross the squeak area limit. However, in the automotive field and particularly in the context of the noise reduction, it is obvious that parameters sets answering the "how to stay in the no-noise area" question

is much more important than the parameters sets answering the "how to cross squeal area to squeak area" question for example.

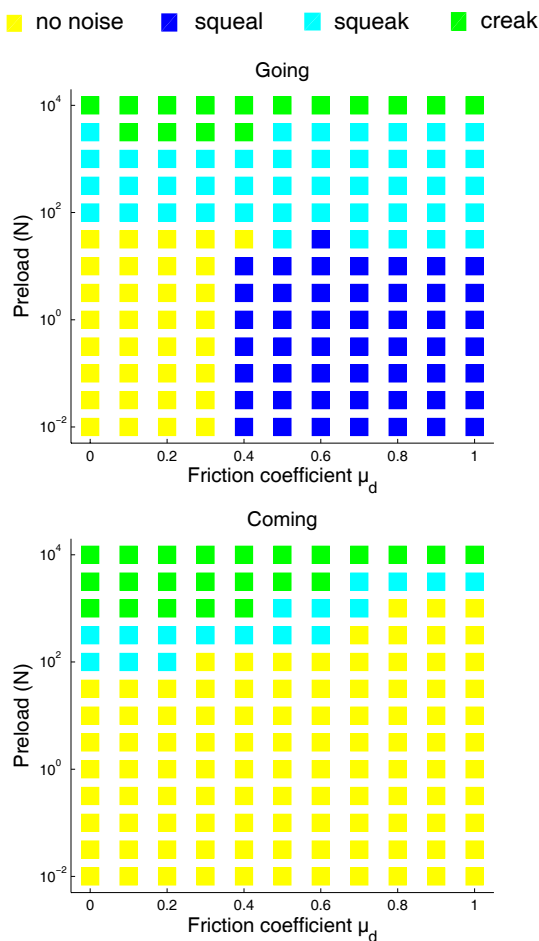


Figure 8: Noise charts - Evolution of noise areas with preload F and friction coefficient μ_d

5 Conclusion

First of all, a database of automotive friction-induced noises has been established. It shows the diversity of perimeters concerned by this issue and also allows a classification by the denominations often used to call these noises, such as squealing, squeaking and creaking noises.

From an experimental side, an exploratory test-rig has been designed. This can generate friction-induced noises with simple structures and automotive materials. Qualitative sensitivity studies have demonstrated the test-rig ability to produce squealing, squeaking and creaking noises.

From a numerical side, a 3 degrees-of-freedom model has been investigated. This model brings together the main physical concepts (stick-slip, sprag-slip, mode-coupling instability) explaining the origin of friction-induced noises, usually independently studied. Three different contact states (stick, slip, separation) have been taken into account for the time simulations performed on this model. These simulations enable to qualitatively obtain the vibrational behaviour at the origin of the squealing, squeaking and creaking noises and highlight the alternation of the contact states when instabilities occur in the system. An algorithm for an automatic classification of vibrational behaviours has also been developed.

This one is based on the proportion and the time evolution of the contact states occurring in the response. Noise charts have been generated thanks to this algorithm. These charts enable to know on which design parameter one can play in order to go from one noise category to another. Non-noisy areas also appear on these charts. Generally, these areas are the one looked for by the industrials.

The prospect is the study of automotive structures and the no more qualitative but quantitative determination of the non-noisy areas for such structures.

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