Multivariate judder behavior analysis of dry clutches based on torque signal and friction material

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***Abstract*—Automotive industries are always concerned to offer more comfort to drivers. In particular, the judder must be avoided as much as possible. Although judder is a very complex phenomenon caused by several factors, this work has focused only on the clutch facing. Based on multivariate statistical analysis and on the torque signal from a real bench test, it has been possible to separate the facings according to their judder performance and manufacturing characteristics. Most importantly, such analysis has been able to establish a gold standard behavior for torque that might be extremely helpful for friction material development, allowing a more consistent understanding of the judder behavior.**

Keywords - facing; clutch; multivariate statistical analysis, friction material.

I. INTRODUCTION

Automotive industries are always concerned to offer more and more comfort to drivers as well as to the passengers of the vehicles. The automated transmission (AMT) is a good example of this industry trend. In AMT there is no clutch pedal and the shifting is done by an automated system, offering more comfort to the drivers, particularly in high traffic jam conditions. However AMT systems are very sensitive to judder. If some vibration occurs during the drive-offs, the driver has no action to reduce judder since there is no pedal to modulate and avoid this uncomfortable sensation.

Judder is a very complex phenomenon that can be caused by many reasons. This study will focus only on the influence of the friction material on judder. In this particular context, it is mandatory that the friction materials, used for both manual and automated transmissions, offer stable friction levels in different tribology conditions like speed, temperature, pressure, etc., in order to reduce the risk to excite the transmission of vehicle and, consequently, causing judder.

The development of a friction material with such a stable friction is a challenge for materials engineers due to the wide range of raw materials selection and process parameters that can be used to produce the facings. However, correlations between these features to judder issues have not been fully understood yet. In fact, a number of studies have been conducted in order to analyze the influence of the friction behavior on judder. Gregori and Domingues [1] have showed recently a significant statistical correlation between friction *versus* relative velocity of slipping with judder in vehicles. In the past, the work by Crowther et al. [2] has also showed the influence of the friction behavior concerning to the judder issues based on car drive-offs simulation. In short, these works have reported that when friction increases with the decrease of the relative slipping velocity, depending on the velocity gradient, a very intense judder could appear in the vehicle. Although the methodologies proposed are simpler, cheaper and faster to apply than the real vehicular tests to predict judder, the analysis of friction gradient or the torque may not be detailed enough to predict the complexity of the judder phenomenon and might lead to inaccurate interpretations.

Nowadays, friction materials have been developed with improved characteristics to reduce judder, based on new resins, fillers, additives, fibers, etc. In fact, a more precise and detailed technique must be developed in order to speed up the facings development. Therefore, the aim of this work is to propose and implement a new methodology, based on multivariate statistical analysis, to efficiently predict judder behavior through the torque signal of different facing materials obtained on a real bench test.

II. CLUTCH SYSTEM

The main function of a clutch system is to engage and disengage the engine to the gearbox for shifting gears, with most comfort for the drivers as possible.

Basically, a clutch system can be divided into three parts: clutch cover assembled, disc and releaser system. Figure 1 illustrates a clutch cover with its main parts highlighted. The clutch cover applies the normal force on the disc by the diaphragm spring. The disc is connected to the gearbox by the input shaft and the torque T is transmitted when the clutch is engaged, calculated by the following equation [3]:

$$T = F \times \mu \times i \times \overline{r} \qquad \textbf{(1)}$$

where F is the normal force (diaphragm spring), μ the coefficient friction, i the number of surfaces contact and $\overline{r}$ the average ratio of the facing.

The diaphragm spring is responsible for the clamp load and the pressure plate for applying this force on the disc. Considering a good level of friction between the disc and the pressure plate, the torque can be transmitted from the motor to the gearbox.

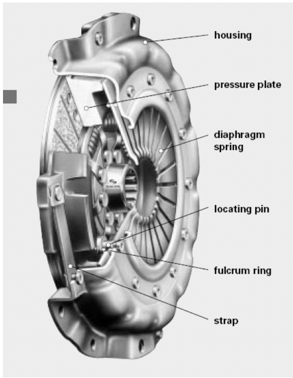

Fig. 1. A clutch cover assembled [4].

A. Some Details of the Facing

Facing is the part of the disc responsible for the transmission of the torque from the engine to the gearbox by the coefficient of friction and is usually composed of thermoset resins (e.g. phenolic), rubber, fillers and fibers like glass, metallic and polymeric. Figure 2 shows a disc of a dry clutch where the facing is normally fixed by rivets, as illustrated in Figure 3.

In general, the facing is produced from 160 mm to 430 mm outside diameter, depending on the vehicle size.

The most important characteristic of the facings is the reliable level of friction in different work conditions of the vehicle.

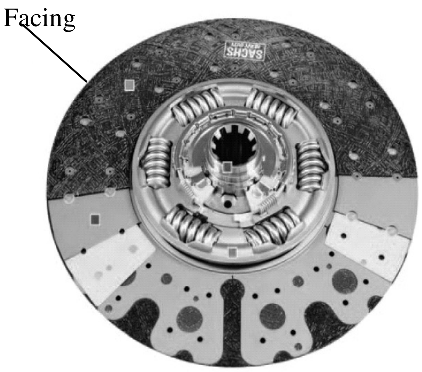

Fig. 2. A clutch disc [4].

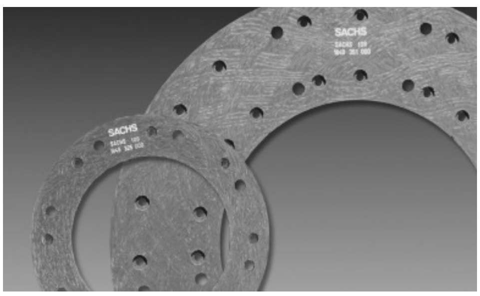

Fig. 3. Details of a facing.

B. The Judder Behavior

Clutch judder [5] is the term used to describe longitudinal oscillation during the clutch slip phase in vehicles when accelerating. The frequency of such automotive behavior ranges from 2.5Hz (heavy truck) to 14 Hz (passenger car) and corresponds to the lowest natural frequency of the driveline.

Figure 4 shows a typical clutch judder problem measured directly in the car, where the longitudinal acceleration reaches an accelerometer close to 1 m/s². The line **A** highlighted stands for the temperature of the bell housing, whereas line **B** is the longitudinal acceleration measured by specific accelerometer on the seat, **C** is the flywheel rotation and **D** is the clutch disc rotation (input shaft of the gear box).

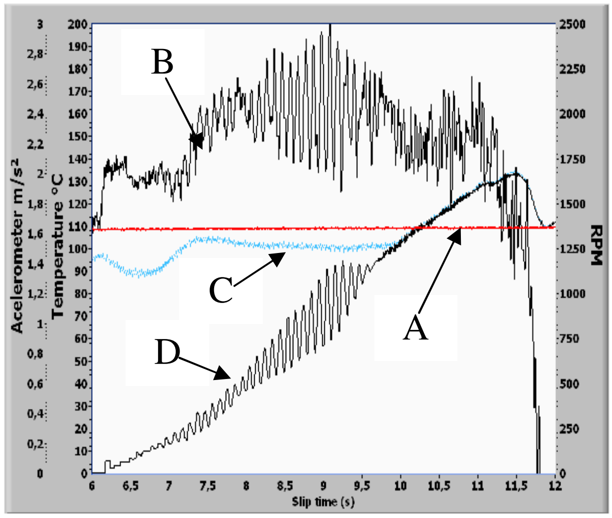

Fig.4. An example of a judder measured in the car: A) Bell housing temperature; B) Longitudinal vibration; C) Flywheel rotation; D) Clutch disc rotation.

III. MATERIAL

In this work, a standard bench test was used [3] to evaluate the durability and determine the friction characteristics of the facing. All experiments have been carried out under the following technical specifications and simulations:

(1) Inertia – 2 kgm²;
(2) Rotation – 0 to 1500 rpm;
(3) Clutch size 200 mm;
(4) Clamp load up to 2000 N;
(5) Number of clutches – 01;
(6) 03 channels for temperature measurements with slip ring; Sensor PT 100; Range 100 – 300°C;
(7) Torque sensor – 500 Nm brush less technology with filter of 200 Hz;
(8) Automatic data acquisition via computer; Sample rate up to 200 Hz; Analog input of resolution 16 bits;
(9) Electric motor 76 kW.

Figure 5 shows a picture of the bench test used here from ZF do Brazil. It is composed of the following 4 main parts: (1) Inertia that simulates the work conditions of the clutch; (2) Torque sensor, where the torque is measured; (3) The clutch test specifically; and (4) The electric motor.

Fig. 5. Bench test used in this work (from ZF do Brazil).

The previous Figure 4 described graphically a real drive-off in the car. However, an example of a drive-off simulated in the bench test is illustrated in Figure 6. It could be, for instance, a drive-off of the car in the traffic light, where the yellow line (1) shows the speed of the combustion engine of the car at 1500 rpm and the green one (2) the speed of inertia being accelerated, simulating, in this case, the input shaft of the gear box. The white signal (3) is the torque being transmitted by the clutch, that is, our signal of interest here. Lastly, the red line (4) describes the temperature of the clutch, measured inside the pressure plate by the PT-100 sensor.

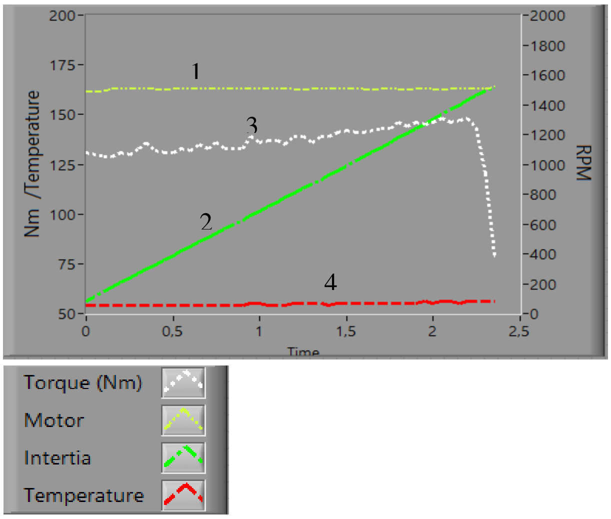

Fig. 6. Simulation of the drive-off in the bench test.

Although the test procedure involves several drives-offs simulations at different temperatures, this work focused on the torque signal after a thermal stress of the clutch, known as the most critical condition for judder behavior analysis [1].

The torque signal of four distinct facing materials has been analyzed, as shown in Table 1. The facings were labeled according to its manufacturing process and resin content. The processes identified as I and E are essentially related to the way of how the binder (composed of thermoset resins, rubbers and fillers) is incorporated to the fibers. Resin content refers to the amount of resin present in the facing chemical formulation.

Facing	**Manufacturing process**	**Resin content**
A	I	Low
B	I	High
C	E	High
D	E	Low

Table 1: Facing characteristics.

IV. MULTIVARIATE STATISTICAL ANALYSIS

In statistical pattern recognition, the decision-making process consists of assigning a given pattern with m features values $x=[x_1,x_2,\ldots,x_m]^T$ to one of g groups or classes $\pi_1, \pi_1,\ldots, \pi_g$ on the basis of a set of measurements or observations obtained for each pattern. In this work, the observations are represented by the torque signal of the facing transmitted by the clutch system.

A well-known multivariate statistical method that identifies the most discriminant linear directions for separating sample groups is the Linear Discriminant Analysis (LDA) proposed originally by Fisher [6]. Let the between-class scatter matrix S_b be defined as

$$S_b = \sum_{i=1}^{g} N_i(\bar{x}_i - \bar{x})(\bar{x}_i - \bar{x})^T \qquad \textbf{(2)}$$

and the within-class scatter matrix S_w be defined as

$$S_w = \sum_{i=1}^{g}\sum_{i=1}^{N_i}(x_{i,j} - \bar{x}_i)(x_{i,j} - \bar{x}_i)^T \,, \qquad \textbf{(3)}$$

where $x_{i,j}$ is the m-dimensional torque signal j from facing π_i, N_i is the number of torque signals from facing π_i, and g is the total number of facings. The vector $\bar{x}_i$ and matrix S_i are respectively the unbiased sample mean and sample covariance matrix of class π_i [6]. The grand mean vector $\bar{x}$ is given by

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{g} N_i\bar{x}_i = \frac{1}{N}\sum_{i=1}^{g}\sum_{j=1}^{N_i} x_{i,j} \,, \qquad \textbf{(4)}$$

where N is the total number of torque signals, that is, $N = N_1 + N_2 + \cdots + N_g$.

The main objective of LDA is to find a projection matrix P_{lda} that maximizes the ratio of the determinant of the between-class scatter matrix to the determinant of the within-class scatter matrix (Fisher's criterion), given by

$$P_{lda} = \arg\max_{P} \frac{\left|P^T S_b P\right|}{\left|P^T S_w P\right|} \,. \qquad \textbf{(5)}$$

However, since the within-class scatter matrix S_w is a function of $(N-g)$ or less linearly independent vectors, its rank is $(N-g)$ or less. Therefore, S_w is a singular matrix if N is less than $(m+g)$. To avoid it here, because $N << m$, we have calculated P_{lda} by using a Maximum uncertainty LDA-based approach (MLDA) that considers the issue of stabilizing S_w with a multiple of the identity matrix [7].

Once the projection matrix P_{lda} has been computed it can represent the most discriminant features of the torque signal x_j as follows:

$$x_j^* = (x_j - \bar{x})^T \times P_{lda} \qquad \textbf{(6)}$$

where x_j^* is the (g-1)-dimensional representation of the original signal on the MLDA space.

V. EXPERIMENTAL RESULTS

Table 2 presents the results from judder tests performed in the vehicle during a thermal stress of the clutch after several drive-offs on uphill practice.

Materials	Judder evaluation after thermal stress of the clutch	Longitudinal Acceleration (m/s²)
A	10	< 0,2
B	5	1,77
C	6	1,2
D	7	1,44

Table 2: Vehicular test results.

Table 3 describes the criteria used during the vehicular test evaluation [3, 5]. This evaluation can be conducted using either a subjective technique or by measuring the vehicle acceleration, or even both. The subjective evaluation is usually performed by an specialist driver capable of classifying the judder sensitiveness according to a standardized scale [3, 5]. The vehicle acceleration is measured by an accelerometer, normally located on the vehicle seat to analyze an analogous discomfort experienced by the driver. For example, during the test facing A has been graded 10 in the subjective evaluation. It means that no driver shall complain about judder. On the other hand, facing B has been graded 5 meaning that there is a possibility that any driver, even a non-specialist one, might notice and complain about judder.

Moreover, it is possible to see from Table 2, particularly when facings B and C are compared to each other, that the difference in the judder behavior might be quite small. It is fair to say that the decision of which facing has the best judder performance based on these results is complicated, making it difficult to decide more consistently the optimal option available.

Max m/s²	0,4	0,7	1	1,4	2	2,7	3,5	4,5
Min m/s²	0,2	0,5	0,8	1,1	1,5	2,1	2,8	3,6
Evaluation index	10	9	8	7-6	5	4-3	2	1
	Acceptable				Limit	Not Acceptable		
Checked by	No Driver	Specialized Driver		Critical Driver		Majority Driver		All driver

Table 3: Criteria for evaluation [3].

Figure 7 shows the original torque signals acquired at the bench test of the four distinct facings considered for MLDA analysis. The horizontal axis shows the variables observed during the drive-offs in the bench test and the vertical axis describes the torque measured directly by the torque sensor with a frequency of 20 measurements per second (20Hz). It is possible to see that the original torque signal is a complex pattern and by analyzing the graphic showed in Figure 7 only has been practically impossible to elucidate which process and resin content most influence the torque signal.

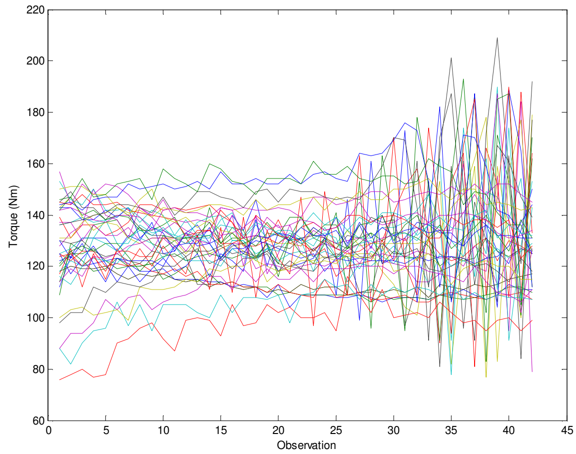

Fig. 7 Torque signal of the 4 distinct facings investigated.

Figure 8 plots the MLDA analysis of the torque signals showed in Figure 7. In projection 1, MLDA clearly separates A and B facings from C and D. The interpretation is that these two groups have been separated by the process - facings A, B (process I) and C, D (process E). In the second projection, MLDA separates facings B and C from A and D. In this projection, these groups have been separated by the resin content, that is, facings B and C have high resin content whereas facings A and D have low resin content. Most importantly, MLDA could also discriminate facing A (blue), which is known to achieve the best performance in the vehicular test (graded 10 in the subjective evaluation) and could be considered as a gold standard in further multivariate statistical tests.

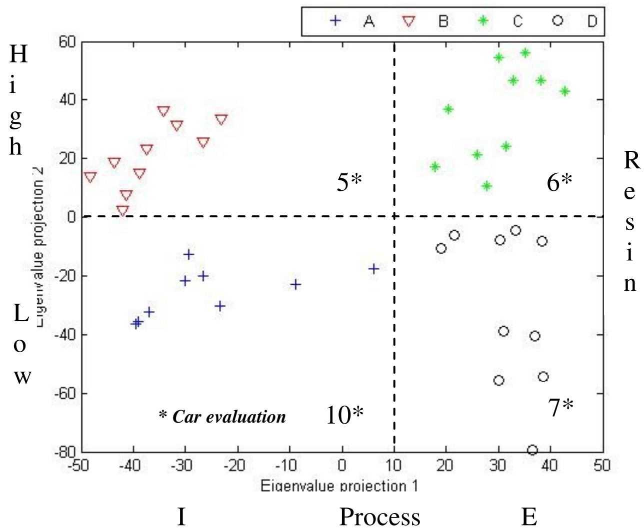

Fig. 8. MLDA analysis of the torque signal.

To validate numerically this multivariate separation of torque signals, we have adopted a cross validation method [6] from the drives-offs samples simulated. For each material 10 drives-offs were randomly evaluated, 8 for training and 2 for testing. This validation procedure was repeated 10 times for all four materials (A, B, C and D). Throughout all the results the Euclidean distance to the nearest neighbor [6] sample has been used to assign a test drive-off to one of the facings learned.

Figure 9 illustrates an example of drives-offs used for the statistical pattern classification considered in this work. It is clear that most sample materials have been correctly classified according to their specified groups.

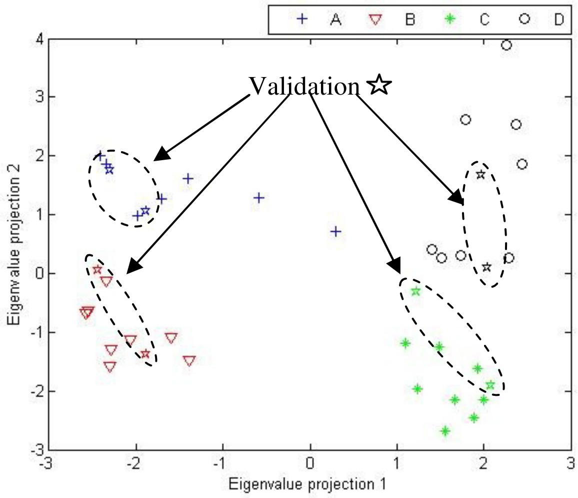

Fig. 9. Plot of testing samples.

Table 4 summarizes the average classification accuracy (and error) of each material due to the aforementioned cross validation. Despite the material C, all other materials have been classified with high accuracy (≥ 85%). Clearly, the material D is the most discriminant one, followed by the materials A and B. Additionally, given the confusion matrix [6] highlighted by Table 5, the material A (Gold) has been 10% misclassified on average as material D and 20% samples of material B on average have been discriminated as the material A. Therefore the torque signals of the material B seem to be the most similar ones to the gold pattern A, but since the materials A and B have the same manufacturing process it would be definitely interesting to investigate the behavior of material B when reducing its resin content to the material A facing levels.

Material	**Average accuracy (%)**	**Error (%)**
A (Gold)	88	6,7
B	85	8,2
C	75,5	12,1
D	100	0

Table 4: Average classification accuracies of all materials.

Material	**A**	**B**	**C**	**D**
A(Gold)	90	-	-	10
B	20	80	-	-
C	-	-	80	20
D	-	-	-	100

Table 5: Confusion matrix.

VI. CONCLUSION

In this work, we have showed that the MLDA multivariate statistical analysis approach has been effective to separate the torque signal according to judder performance, as well as the characteristics of the facings given the resin content and manufacturing process.

More specifically, MLDA could separate the 4 facings under investigation and specially discriminate the facings A and D, which have been the ones that showed the best performance in the vehicular test. Since the methodology proposed explores in more details the torque signal, we believe that this study might allow a fine tuning in the chemical formulation of the facing, improving the judder performance in general, once that only by the results from the vehicle could be difficult to choose the better facing for optimization, because some evaluations are very similar.

It is important to note, however, that the knowledge about the products analyzed in this study is crucial because the interpretation of the MLDA considerably depends on the engineer's expertise.

As future works, we intend to increase the sample rate to 200Hz to allow a better torque signal resolution and carry out the multivariate statistical analysis using more observations and different critical condition for judder behavior represented not only on the time domain, but also on the frequency one.

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