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Link between objective and subjective characterizations of Bb Clarinet reeds

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Abstract

This paper deals with the subjective and mechanical characterizations of single cane reeds. Subjective tests performed by a single expert gave an estimation of the subjective descriptors “*ease of playing*”, “*brightness*”, “*roundness*”, “*projection*” and “*global quality*”. The mechanical characterization involved measurements of static compliance, dynamic compliance, resonance frequency and Q factor of the first vibration mode. Two sets of clarinet reeds were studied. The first set contained 50 reeds identical in cut, brand and strength. The second set contained 150 reeds with 3 different cuts but identical in brand, strength and static compliance. Results show that the perceptual space is almost bi-dimensional for the first set of reeds and mono-dimensional for the second set. For the first set, the two dimensions were largely created by the descriptors *ease of playing* (highly correlated to *brightness*) and *roundness*. For the second set (with a constant static compliance), the main dimension was created by all the descriptors, that are correlated. The study of correlation coefficients between subjective descriptors and mechanical parameters shows that the static and dynamic compliance are correlated with the descriptor *ease of playing* for set 1. For set 2, the correlations are too low to make a link between the perceptual space and the objective parameters.

Keywords: Musical acoustics, clarinet, reed, subjective tests, mechanical characterization
2010 MSC: 00-01, 99-00

1. Introduction

The musical quality of woodwind instruments such as the clarinet or the saxophone depends strongly on the reed quality. Today, musicians use the strength of the reed (indicated on the box by a number or letter), along with the type of cut, to choose a reed that suits

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their mouthpiece and playing. However, the mechanical properties of single cane reeds with the same strength and same cut may vary from one reed to another, which lead to differences in the playability and in the sound perceived by the player and listener.

The following questions were raised :

- is it possible to distinguish perceptively reeds with the same strength, assuming that the strength is measured accurately ?
- is it possible to explain perceived differences using physical parameters other than the strength ?

Currently, experimental characterization of reed mechanical properties by reed makers is performed by measuring the mechanical stiffness, the reed being submitted to a static force at a particular location from the tip. This measurement enables an estimation of the reed strength which is indicated on the box for the clarinet or saxophone player. This method is considered necessary to sort reeds of different strengths and to indicate to the musician whether or not a reed can be played with a particular mouthpiece. However, this approach cannot explain the great differences perceived by musicians between reeds with the same strength and the same cut [1].

The aim of the present work is to try to make the link between the physical properties of a reed and subjective descriptors.

The objective characterization of a reed's physical properties has been studied using different approaches (visualization of cane cells, mechanical measurement of vibration response, optical holography to identify the vibrational modes of the reed). Kolesik [2] studied the anatomical characteristics of cane using confocal laser scanning microscopy. Mukhopadhyay et al. [3] proposed to characterize the quality of saxophone reeds using planar electromagnetic sensors. Obataya et al. [4] studied the effect of relative humidity on the dynamic Young's modulus of the reed using a free-free beam flexural vibration method and by measuring small plates made with cane. Pinard et al. [5] observed the vibrational modes of 24 clarinet reeds in both dry and wet conditions using holographic interferometry. Picart et al. [6] observed the modes of a clarinet reed using holography and measured the displacement of the reed tip during auto-oscillations created in an artificial mouth. Taillard et al. [7] studied the mechanical behaviour of reeds using holography. These experiments have enabled a better understanding of the reed material parameters and the effect of these parameters on the reed vibration, but they do not make the link between mechanical parameters and the subjective evaluation by

the musician.

The subjective characterization of reeds has been the subject of fewer studies. Recently, Petiot *et al* [1] conducted an experiment with 20 tenor saxophone reeds of identical brand and cut played by 10 saxophone players. The musicians were asked to evaluate the *ease of playing*, the *brightness* and the general quality of the reeds. In parallel, different signals (mouth pressure, acoustic pressure at the saxophone bell) were recorded during saxophone playing and different playing parameters were estimated. Results show that there is a noticeable agreement between the musicians for the descriptors "*ease of playing*" and "*brightness*", whereas the "*global quality*" descriptor leads to important inter-individual differences. The study of correlations between the subjective descriptors and the objective parameters reveals that the *ease of playing* is correlated with the threshold pressure and that the subjective *brightness* is correlated with the spectral centroid of the acoustic pressure. Predictive models of the "*ease of playing*" and "*brightness*" using the objective parameters in playing conditions are proposed and show interesting performances. However, there are still no objective parameters related to the reed mechanics that are clearly representative of the subjective dimensions described by players.

The aim of the present work is to explain by physical measurements why particular reeds with the same strength (which corresponds to common playing conditions) produce different sounds (more or less bright) and provide different feelings for the player in terms of their playability (more or less easy to play). In this study, each reed is measured dry and the hygrometry, which can lead to important physical changes as shown by Taillard [7], is not controlled. However, we assume that differences in reed quality are greater than the differences due to hygrometric variations. Finally, it is assumed that large differences in reed quality remain constant over long time periods.

In order to measure reed parameters, two systems are used. First, to measure the parameters under static conditions, a static bench was developed by the reed manufacturer. Meanwhile, to measure the parameters under dynamic conditions, a vibroacoustic bench has been developed. This system is designed so that it could be used in a factory where many measurements must be done easily. It is based on the measurement of the vibroacoustic response of reeds free to vibrate without any mouthpiece nor artificial lip.

On the other hand, subjective tests have been conducted with a single expert musician in order to assess the reeds according to subjective descriptors. The study of correlations

between objective parameters and subjective descriptors enables a performance assessment of the vibroacoustic and static measurement benches for predicting the subjective descriptors.

Section 2 of the paper reviews the physical parameters which could potentially explain how a musician perceives a reed when playing (both in terms of playability and sound produced). Section 3 presents two mechanical systems used for characterizing reeds as well as the subjective tests that were conducted using two different reed sets. In the last section, the subjective descriptors are analyzed and the correlations between these descriptors and the mechanical parameters are discussed.

2. Background

The aim of this section is to describe the role of the reed in the functioning of the instrument and to define which mechanical parameters should be considered in order to predict the subjective parameters.

2.1. Physical Quantities

While playing, a clarinet player receives different information as a result of his/her interaction with the instrument and the environment (room) as shown in figure 1. In this situation, the player gets feedback from :

- the mouth pressure
- the lip pressure
- the radiated sound (direct) and reverberant field due to the room acoustics
- the vibrations of the mouthpiece inducing bone conduction and the bore vibrations (sensed by the hands)

In the context of a simplified mouthpiece model, the main physical parameters which govern the functioning of the instrument itself are (see figure 2) :

- p : acoustic pressure in the mouthpiece
- P_m : mouth pressure
- y : reed tip displacement
- U_i : volume flow velocity entering the mouthpiece
- U_r : volume flow velocity induced by the reed movement
- U : volume flow velocity entering the bore
- H : opening of the reed at rest with the lip pressure

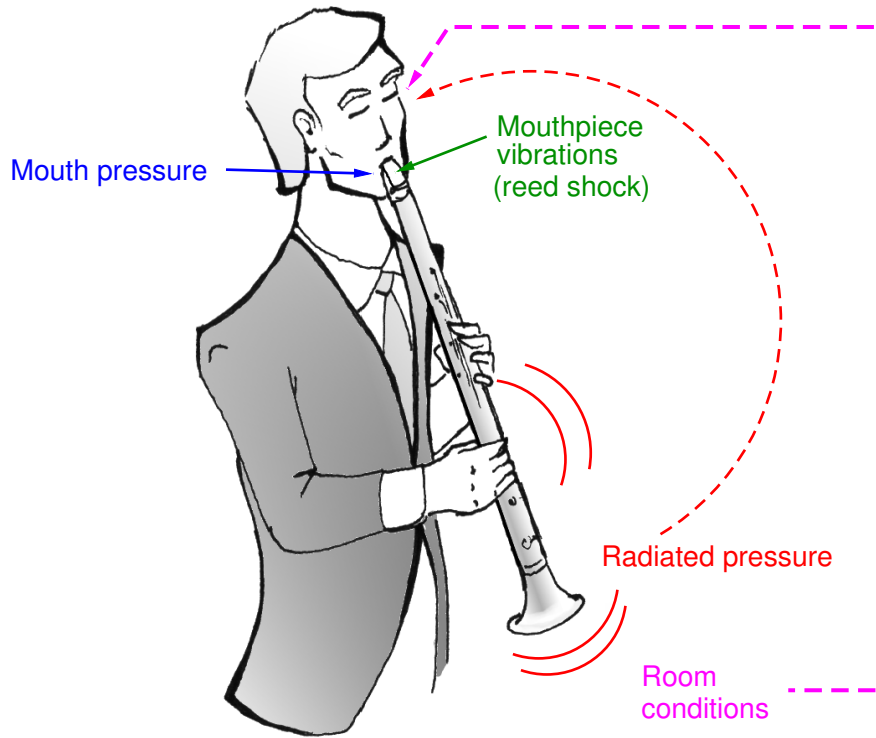


FIGURE 1: Information received by the clarinet player while playing.

— H_0 : opening of the reed at rest without lip pressure

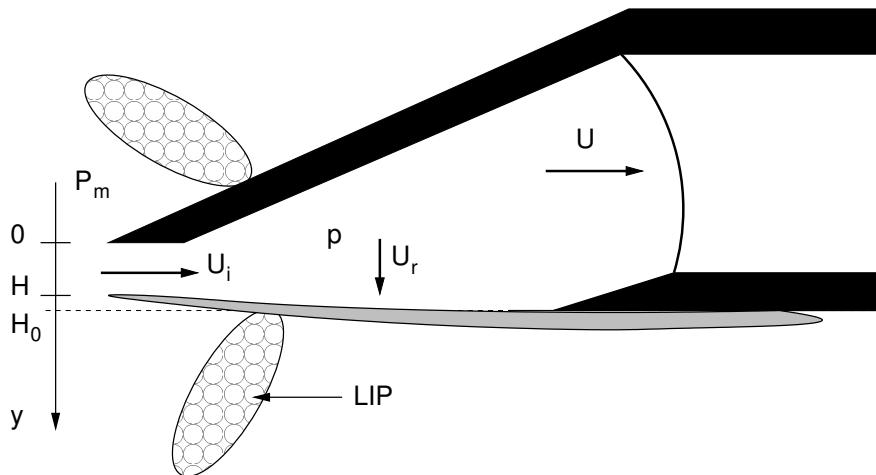


FIGURE 2: Schematic view of the physical parameters used to describe the reed motion.

Assuming a lumped element model for the reed, the usual reed parameters are the effective mass M , effective damping R , and effective stiffness K as shown for example in [8]. Moreover, the reed volume velocity U_r , defined by $U_r = S_r \frac{dy}{dt}$, where S_r is the reed effective area, can be taken into account.

2.2. Effects of reed on playing parameters

The aim of this section is to recall the link between the reed and mouthpiece parameters (mass, damping, stiffness, reed tip opening, effective vibrating area) and the physical parameters (called playing parameters) which govern the clarinet player's perception (figure 3).

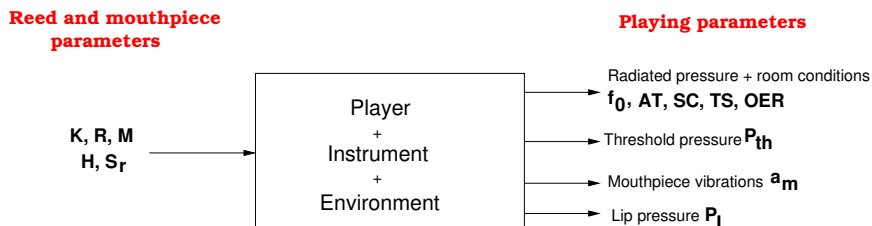


FIGURE 3: Systemic representation of the clarinet playing (input - output).

The physical parameters which *a priori* govern the perception of the player are :

- the fundamental frequency of the perceived sound f_0 , related to the frequency of the oscillation signal (pressure in the mouthpiece)
- the threshold pressure P_{th} [9], which is the minimum pressure in the mouth that the musician needs to supply in order to play the instrument, which is probably related to the ease of playing perception [1]
- the lip pressure P_L used by the musician to change the reed opening H and effective area S_r
- the properties of the perceived sound (related to the radiated pressure and to the room conditions), which can be described by different objective parameters as explained in [10, 11]. The radiated pressure is directly related to the acoustic pressure in the mouthpiece and to the radiation properties of the instrument. According to Barhet [12], for a clarinet player the important parameters are the attack of the tones (Attack Time AT), the spectral richness (Spectral Centroid SC , third Tristimulus coefficient TS), and the irregularity of the spectrum (Odd/Even Ratio OER),
- The properties of the sound perceived by bone conduction, *a priori* related to the acceleration a_m of the mouthpiece, due to the beating of the reed on the lay as observed in [6]

The reed stiffness K is a major parameter that affects the playing frequency [13, 14, 15] and the threshold pressure [16, 17, 18, 19]. The reed mass and damping may also affect to a lesser extent the threshold pressure [20]. Finally, the timbre of the clarinet depends on the

reed resonance frequency [21, 22, 23] and on the extent to which the reed beats against the mouthpiece lay (observed numerically [24] and experimentally [25]).

These results show that the reed properties affect the playing in different ways. However, the relationship between reed mechanical parameters and subjective descriptors is not well established yet. The following sections aim at investigating the relationship between objective parameters describing the reed mechanics and subjective descriptors.

3. Materials and methods

This section presents the two methods used for measuring the reed mechanical parameters as well as the subjective tests performed to derive subjective descriptors.

3.1. Basic assumption of the study

The results of previous studies (§2) show that the linear reed parameters (stiffness, mass, damping) while playing, plus the beating of the reed against the mouthpiece lay, affect the playing parameters (threshold pressure, timbre, vibrations).

As we wish to explain subjective descriptors along with reed mechanical parameters measured during the manufacturing process, we assume in this study that the linear parameters of the reed alone (not in a playing situation) can affect the playing parameters.

3.2. Reed static characterization

In this section, we present the principle of the static measurement bench which enabled us to measure the static compliance StC of the reed used in this paper. The static compliance is used to deduce the strength of the reed (range 1 to 5) defined by the manufacturer on the reed box and used by the musician.

The reed static compliance is measured using a flexural bench as follows. The reed is maintained on a plate with a screw pressing the stock (the geometry of the reed is defined in Figure 4). The vamp of the reed is bent using a spring with a known stiffness. Therefore, a known displacement of the spring imposes a known force on the reed. At the same time, the displacement of the reed tip is measured at a distance x from the reed tip (with $x \in [2, 5]$ mm depending on the reed cut).

This measurement enabled us to deduce the compliance (inverse of the stiffness), defined as the ratio between the measured displacement and force at the reed tip. The compliance range is from 8 (very hard reeds, strength = 5 or strength = “H”) to 24 (very soft reeds,

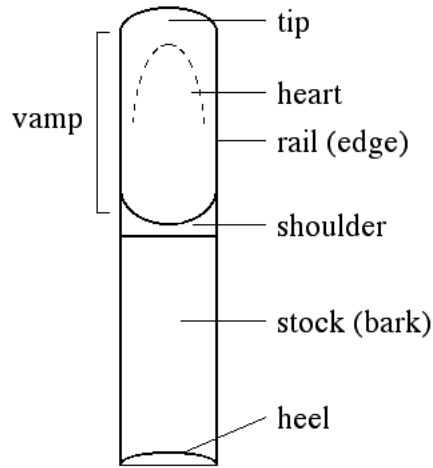


FIGURE 4: View of the different parts of the reed (from [26]).

strength = 1 or strength = “S”). As the static bench is not calibrated, this compliance is given in arbitrary units.

3.3. Reed dynamic characterization

The vibroacoustic (VA) measuring bench enables a characterization of single cane reed mechanical properties. An important feature is that this bench could be used for industrial applications. For this reason, this bench does not use any artificial lip nor any mouthpiece as presented in previous work [27].

3.3.1. Principle of the VA bench

The vibroacoustic bench is shown in figure 5. It excites the single cane reed with an acoustic field and measures the reed tip displacement at different points.

The measuring bench is composed of the following parts :

- A plate which controls the vibrating length of the reed and the dimensions of the gap around the reed boundary. In this experiment, the vibrating length is 30 mm and the width of the gap is 1 mm (see figure 5)
- A clamping system made of a linear support equipped with a spring that applies a force on the reed. The position of the linear support can be modified along the x axis.
- An acoustic system composed of a loudspeaker (tweeter) placed in the back cavity (volume $\sim 4\text{cm}^3$) and excited with a sweep signal.
- A displacement sensor Philtec RC25 [28] measuring the reed displacement. This sensor can be displaced in the longitudinal (x) and transversal (z) directions in order to

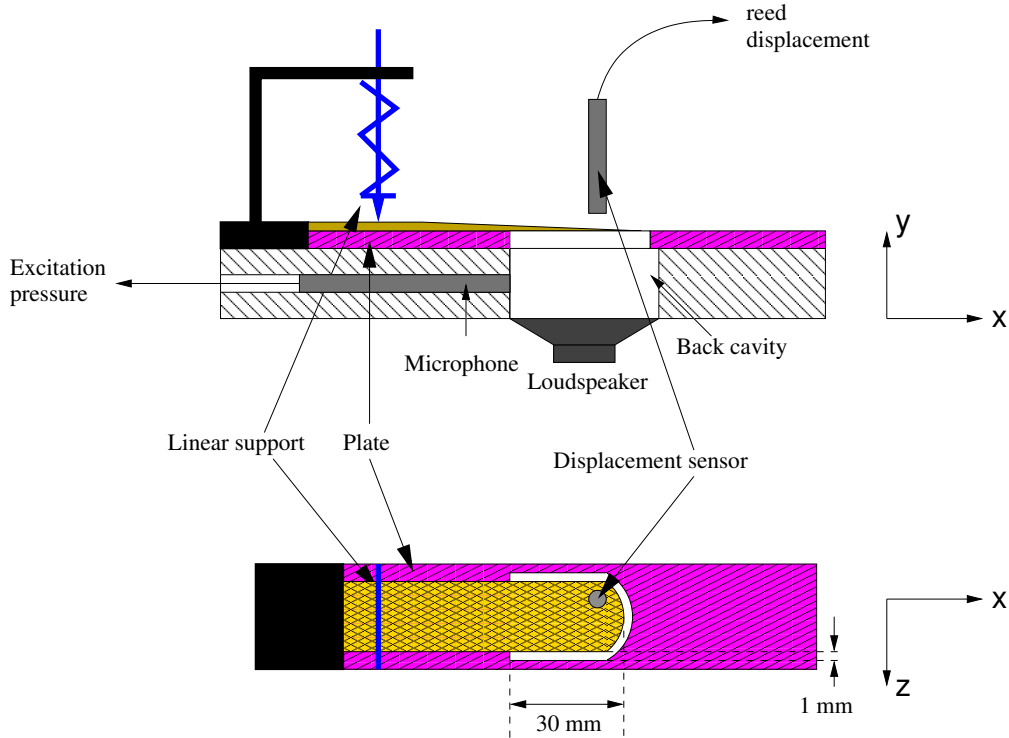


FIGURE 5: Description of the vibroacoustic bench (VA bench) (front and top view).

measure different points. It can also be moved in the vertical (y) direction in order to use the linear region of the sensor sensitivity, the optical sensor being non linear.

- A 1/4 inch microphone placed in the back cavity near the reed in order to measure the excitation pressure. The dimensions of the back cavity enables to assume constant pressure in the cavity up to $6kHz$.

The equivalent reed parameters are estimated by measuring the reed response y_i/p , where y_i is the displacement of a point i of the reed and p is the acoustic excitation pressure in the cavity, assumed to be homogeneous. Three reed responses H_m^i (m for “measured”) are measured for three points placed on the reed tip (left, center, right) as shown in figure 6. According to the displacement sensor dimensions and to the time needed for measuring the different reeds (up to 150 reeds for one experiment), it was assumed that three points enabled to study the transverse vibration behaviour of the reeds. However, the analysis of the transverse modes did not give any relevant results so that the three transfer functions obtained at the three points are used for estimating the first mode properties only.

An example of the measurement results is given in figure 7 for a vibrating length of 30 mm. It shows that the first vibration mode (first flexural mode) is around 2000 Hz and that

it is predominant (60 dB greater than the amplitudes of the higher modes). At resonance, the order of magnitude of the reed tip displacement is $1 \mu\text{m}/Pa$. Knowing that the pressure level in the cavity is around 120 dB SPL, the amplitude of the reed tip is around $20 \mu\text{m}$ at the resonance frequency. This shows that the measurement is performed using a smaller displacement of the reed tip than that observed in playing conditions (0.1 to 0.5 mm typically).

The second mode is a torsional mode, the third mode is the second flexural mode and mode 4 is a combination of flexural and torsional effects. These results are similar to those obtained by Taillard [7], the main difference being the number of modes observed.

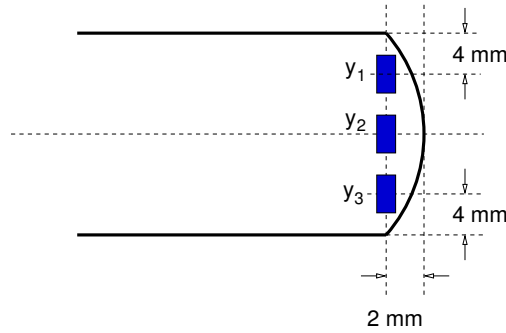


FIGURE 6: View of the three positions used for measuring the reed displacements y_1 , y_2 and y_3 .

3.3.2. Estimation of reed parameters : principle

Given that the reed displacement y_i is measured at three different points ($i = 1, 2, 3$) and assuming a linear behaviour of the reed (no mouthpiece, no lip), the reed displacement can be written as

$$M\ddot{Y} + B\dot{Y} + KY = P, \quad (1)$$

where $Y = \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix}$ is the displacement vector, $P = \begin{pmatrix} p_1 \\ p_2 \\ p_3 \end{pmatrix}$ is the pressure vector, p_i being the excitation pressure at point i , and where M , B , K are respectively the mass, damping and stiffness matrices.

Assuming the excitation pressure is identical at the three points i , the excitation pressure can be written $P = E.p$, where E is the unit vector and p is the acoustic pressure measured by the reference microphone. Using this assumption, the theoretical reed response can be written

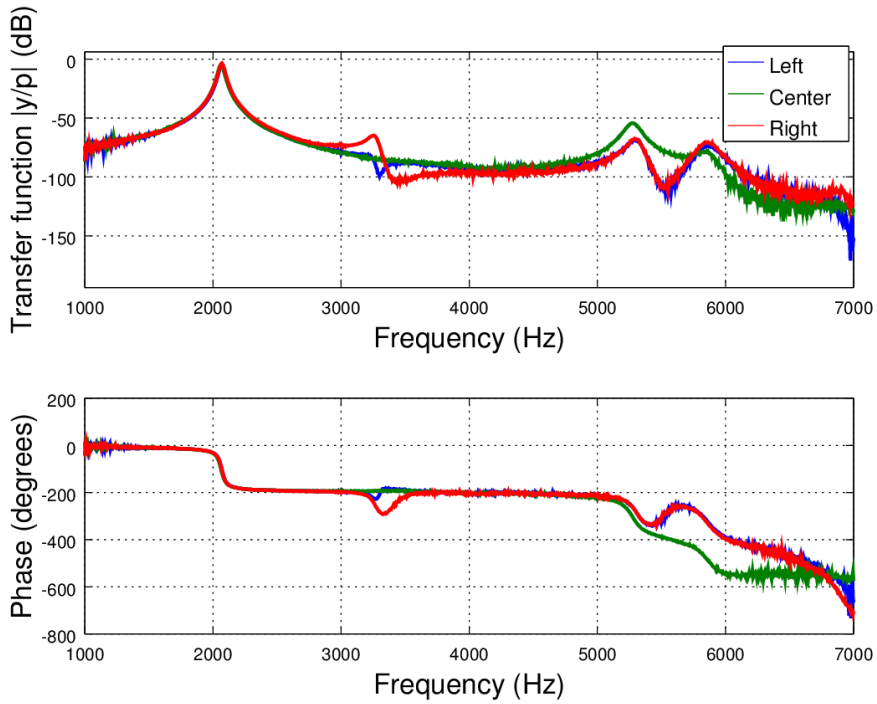


FIGURE 7: Example of reed response measurement H_m^i . The reference for the amplitude level is $1 \mu m/Pa$.

$$H_{th} = \begin{pmatrix} \frac{y_1}{p} \\ \frac{y_2}{p} \\ \frac{y_3}{p} \end{pmatrix}.$$
 Finally, the observation of the measured FRF suggests that the modes are uncoupled (figure 7) so that the reed Frequency Response Function vector can be written as (subscript *th* for theoretical)

$$H_{th} = \sum_{n=1}^N \frac{C_n}{1 + j \frac{\omega}{\omega_n Q_n} - (\frac{\omega}{\omega_n})^2}, \quad (2)$$

where N is the number of modes observed and C_n is the compliance vector for mode n written as $C_n = \begin{pmatrix} c_{n1} \\ c_{n2} \\ c_{n3} \end{pmatrix}$.

Parameters C_n , ω_n and Q_n are estimated by adjusting the theoretical FRF H_{th} to the measured transfer function H_m using a least mean square (LMS) estimator described by Piranda [29]. Figure 8 shows an example of measured and estimated responses.

As the first vibration mode of the reed is predominant (see figure 7), only the parameters of the first mode (C_1 , ω_1 and Q_1) are used. In the next part of the paper, the parameters used for studying the correlation with subjective indicators are :

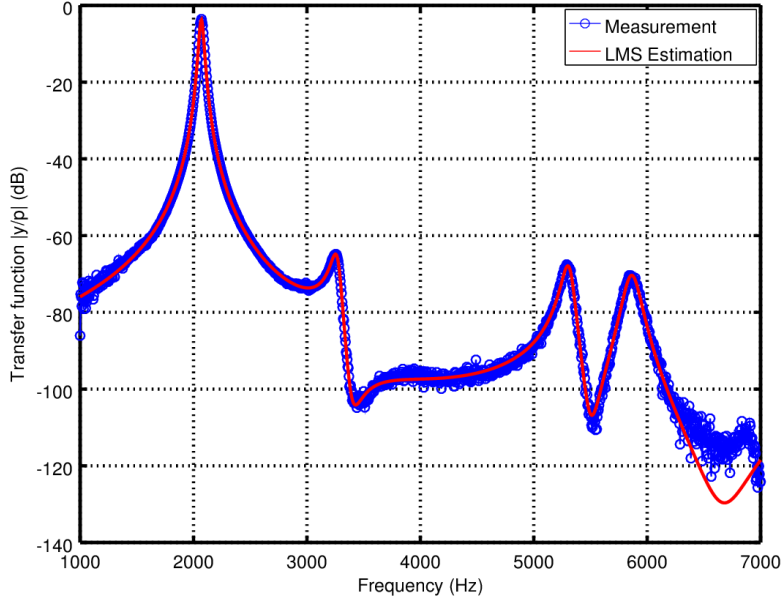


FIGURE 8: Example of transfer function identification using the method described by Piranda [29] (o : measurement H_m , - : theoretical FRF H_{th}). The amplitude reference level is $1 \mu\text{m}/\text{Pa}$.

- the dynamic compliance DyC defined as $DyC = \frac{\sum_{k=1}^3 c_{1k}}{3}$, or average compliance estimated at the three measurement points.
- the first resonance frequency $F_r = f_1 = \frac{\omega_1}{2\pi}$.
- the quality factor of the first resonance $Q = Q_1$.

In the next part, all measurements are done with a reed vibrating length equal to 30 mm. Modal parameters for higher modes were also considered for measuring the correlation between mechanical parameters and subjective descriptors but did not give any relevant results.

3.3.3. Accuracy of the bench

The accuracy of the bench was studied in order to estimate the uncertainty in the reed parameters for the first mode. This value is an indicator of the ability of the vibroacoustics bench to classify reeds in different families.

50 reeds having the same strength and same cut were measured by two operators for two consecutive days (operator 1 during day 1, operator 2 during day 2). For each reed, the relative differences between the 2 measurements (day1, day2) was computed. Then the standard deviation of these relative differences (in %) led to the estimation of the measurement error between the two measurements. For the first mode compliance DyC , the standard deviation

is 2.5%. Assuming that the measurement results follow a normal distribution, the relative error for DyC is estimated to be $\pm 5\%$ with a 95% confidence.

The estimation of uncertainties for the resonance frequency and the quality factor show that the resonance frequency is well estimated, the 95% confidence interval being $\pm 1\%$ for the resonance frequency and $\pm 2\%$ for the quality factor.

3.4. Comparison between static and dynamic measurements

In order to compare the dynamic compliance DyC and the static compliance StC , 50 reeds with variable static compliance between 8 (strength = 5) and 24 (strength = 1) were measured. The result is shown in figure 9. In this measurement, the dynamic compliance value DyC is within the interval 15 – 45 nm/Pa and shows a high correlation between the two measurements ($R \simeq 0.99$). The relationship between the two measurements does not seem to be linear for high static compliance (greater than 20).

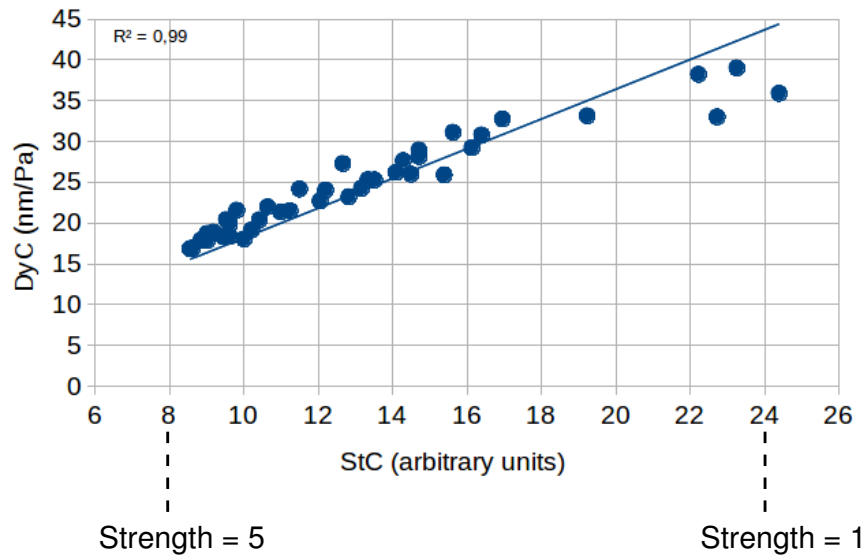


FIGURE 9: Comparison between the dynamic compliance DyC and the static compliance StC for a set of 50 reeds.

3.5. Subjective tests

The aim of the subjective tests was to obtain a reliable quantitative assessment of the perception of different reeds by a musician.

3.5.1. Reed samples

Two sets of Bb clarinet reeds were used for this study. The first set (referred to as “unselected reeds”) contained 50 reeds of the same strength but different static compliance

(variation $\pm 10\%$). The second set (referred to as “selected reeds”) contained 150 reeds of the same strength and approximately identical static compliance (variation $\pm 1\%$).

Finally, when compared with the full range of commercially available reed strengths (from 1 to 5), it can be seen that the compliance variations of these two groups is small or very small (see Figure 10).

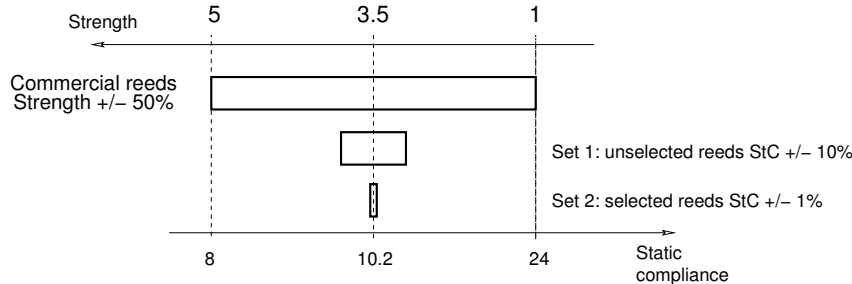


FIGURE 10: Range of compliance variation for commercial reeds (strength 1 to 5), set 1 (unselected reeds) and set 2 (selected reeds).

3.5.2. Procedure

One expert musician participated in the subjective tests. This expert is a skilled clarinet player, working regularly with the reed manufacturer as a professional tester. With only one expert, we are of course aware that it is not possible to generalize the results of the experiment nor to make general conclusions concerning the perception of reeds by musicians. So, the work focuses on an interpretation of the link between the subjective evaluation of a given expert (professional tester) and the mechanical parameters of the reeds. Based on previous studies [27, 1], we propose different subjective descriptors to assess the reeds depending on the reed sets. These descriptors are detailed later in §4.1 and §4.2.

After the reed was mounted on the mouthpiece by an external operator, the musician was asked to play freely to assess all the descriptors (free playing conditions) without knowing the reed type. The evaluation phase used pencil+paper to assess the reeds on graphical quantitative scales. After playing the reed, the expert was invited to put a mark on the rating scale of each subjective descriptor, corresponding to his perceived sensation of the intensity of the descriptor. The mark was next transformed into a quantitative rating by measuring the distance in cm between the left end of the scale and the location of the mark. The reeds presentation order was randomized. 3 repetitions of each reed were proposed, in 3 independent blocks, for a total of 150 evaluations for set 1 and 450 for set 2.

The assessment of this huge number of evaluations has been possible given the particular

abilities of the musician, who is a professional tester. If necessary, the expert was allowed to make slight adjustments of the reed on the mouthpiece, but of course without watching the type of reed used (hidden by the ligature). The consistency of the mounting of the reed was unfortunately not checked, it was only dependent on the ability of the operator. This source of variation is assumed to be weak.

3.5.3. Data analysis

Each descriptor was analyzed using a one-way variance analysis. Reeds were treated as a fixed effect. Differences were considered significant at $p < 0.05$.

The subjective evaluations of the expert were analyzed with classical methods in sensory analysis [30]. The evaluations are quantitative ratings of each product (the reed) according to different descriptors, during 3 repetitions. The objective of the analysis is to understand and describe the differences between the products (the reeds). The first way to analyse the data is to consider each descriptor one by one (univariate analysis). In this case, the analyst wants to know if the differences between the average values of the reeds (across the repetitions) are important enough, given the repetition error. The classical method to perform this analysis is ANOVA (Analysis of variance). Analysis of variance (ANOVA) is a general method to study the influence of one or several factors (with different levels) on a quantitative response [31]. The method belongs to the general frame of the linear model, that proposes to fit a linear model from a set of observations. In our case, the factor under study is the product (the reed, with a number of levels equal to the number of reeds) and the response is the ratings given by the expert for a given descriptor. Assumptions are made according to the fitting error of the model (normal distribution) that allow the definition of statistical tests to decide whether or not the differences between the average ratings are important enough. The classical statistics in ANOVA is the Fisher variable F (or F -ratio) that makes the ratio between the between-reeds variability to the within-reed variability. A statistical test (F -test) on the Fisher variable is carried out, to determine the false rejection probability (p -value or p) of the hypothesis H_0 . In our experiment, H_0 is stated as : All the reeds obtain on average the same ratings (in other words : there is no effect of the reeds on the ratings). For a given significance threshold (5%, or 1%), critical values $F_{5\%}$ (or $F_{1\%}$) can be computed with the Fisher-Snedecor distribution law, considering H_0 true. The next stage of the test is to compare the observed value of F (F_{obs} with the actual ratings) to

the critical values $F_{5\%}$. If F_{obs} is larger than $F_{5\%}$, H_0 can be rejected with a false rejection probability lower than 5%. Another way to present the results of the test is to give the p-value (p) that corresponds to the probability with which $F_{obs} = F_{p\%}$. If p is low, H_0 can be rejected with a very weak risk to take a false decision. The effect of the reeds on the ratings is then considered as significant. ANOVA and the F-test is used in the next section for each subjective descriptor, to detect if the differences in the ratings of the expert are important enough to be significant. The second way to analyse and understand the ratings is to study the differences between the reeds, by considering all the descriptors together (multivariate analysis). The most applied approach for getting an overview of multivariate data is to use Principal Component Analysis (PCA) on the reeds-by-descriptors matrix, after having averaged out replicates. The products are considered as individuals, and the descriptors as variables. PCA provides a transformation to convert variables into a set of uncorrelated principal components. The transformation is defined in such a way that the first principal component accounts for as much of the variability in the data as possible (% of inertia), the succeeding components accounting for the remaining variance in a decreasing way. In this way, a graphical representation of the data can be made in a low dimensional space (2 or 3 dimensions) without much loss of information. This representation is interesting to reveal the underlying structure of the data, to explain the main differences between products and to visualize the correlations between variables. Interpretation of the principal components can be provided by an examination of the correlations between the descriptors and the principal components, and with the projection on the factorial plane of additional variables. In the next section, PCA is used to describe and interpret the subjective ratings for the two sets of reeds. A principal component analysis (PCA) was performed on the correlation matrix of the expert sample means. Objective parameters were plotted on the factorial space as additional variables.

4. Results

4.1. Set 1 : unselected 50 reeds

A set of 50 reeds for Bb clarinet of identical brand, cut and strength (strength = 3.5) was taken from 5 commercial boxes of 10 reeds each. The name given by the makers to the cut of reed that was used in this set is Bb_1 . The static compliance StC was measured using the bench described in §3.2. The static compliance range ($\frac{\max(StC) - \min(StC)}{\text{mean}(StC)}$) in this set was 20%

and the dynamic compliance range was 32%. The variation range defined by 2σ , where σ is the standard deviation, was $2\sigma = 12\%$ for the static compliance and $2\sigma = 15\%$ for dynamic compliance.

4.1.1. Subjective tests

For this set, 3 descriptors were considered :

- *Ease of playing*. Representing an assessment of the ease of producing a sound, rated on a 5-level structured scale : very difficult – difficult – average – easy – very easy (the higher the rating, the easier the reed)
- *Brightness*. Representing an assessment of the overall *brightness* of the sounds produced by this reed, rated on a 5-level structured scale : very dark – dark – neutral – bright – very bright (the higher the rating, the brighter the reed).
- *Roundness*. Representing an assessment of the overall *roundness* of the sounds produced by this reed, rated on a 3-level structured scale : nasal – neutral – round (the higher the rating, the rounder the reed).

The results of the subjective tests on *ease of playing*, *brightness* and *roundness* are presented respectively in figures 11, and 12 and 13. The figures plot the average ratings distribution for the three descriptors. They represent the histogram of the average ratings of the 50 reeds, by considering 9 intervals (bins) for the ease of playing and brightness, and 7 intervals for roundness. To facilitate the interpretation of the histogram, the levels used in the structured scales are mapped onto the corresponding intervals of the histogram.

For *ease of playing*, the expert focused strongly on the level 'easy', for which the estimation error (proportional to the standard deviation of the three evaluations) was much lower than for other levels. For *brightness*, the expert focused less strongly on the level 'Neutral' but the estimation error for level 'bright' was smaller. For *roundness*, most of the reeds were considered as 'neutral'.

Global significant differences between reeds were studied by ANOVA. The F-ratios of the one-way ANOVA are presented for each descriptor in table 1.

Descriptor	<i>ease of playing</i>	<i>brightness</i>	<i>roundness</i>
Reed F-ratio	4.57 (***)	2.75 (***)	2.18 (***)

* $p < 0.05$ - ** $p < 0.01$ - *** $p < 0.001$

TABLE 1: Results of the one-way ANOVA for each descriptor (F-ratio) for the 50 unselected reeds.

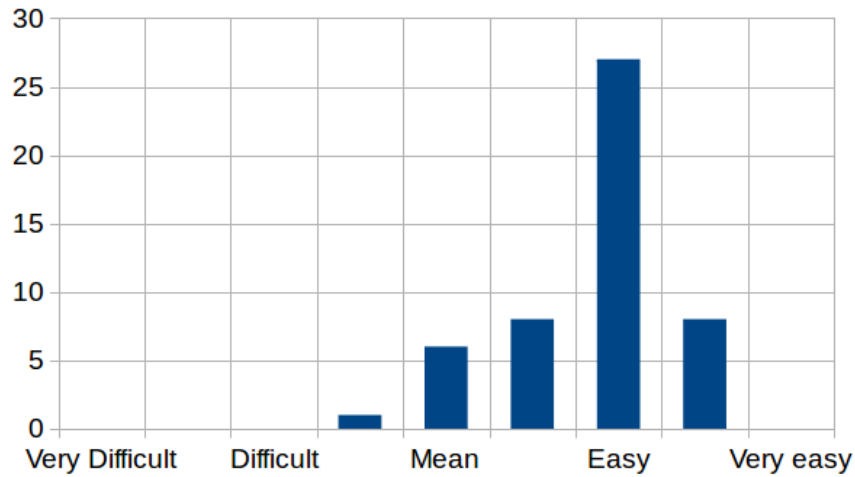


FIGURE 11: Distribution of *ease of playing* mean values for set 1 (50 unselected reeds).

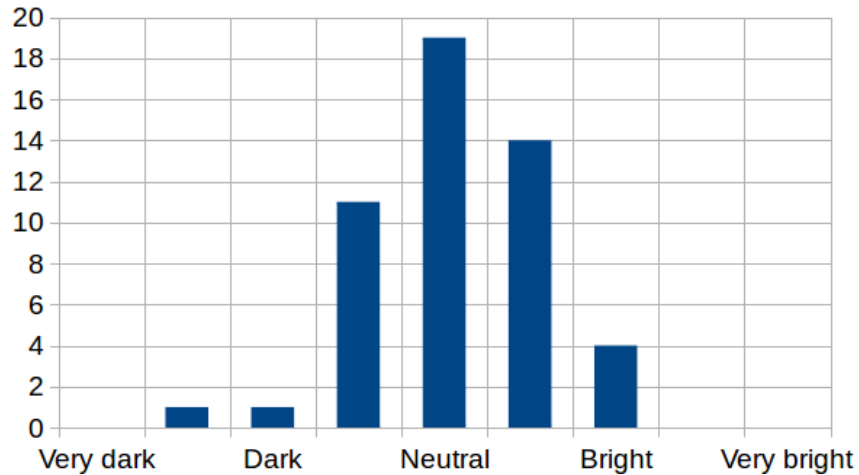


FIGURE 12: Distribution of *brightness* mean values for set 1 (50 unselected reeds).

All the descriptors showed a significant product effect with large F-ratios ($p < 0.001$), the effect being the most important for *ease of playing* and the least important for *roundness*. Given that the F-ratio represents the between-reeds variability to the within-reed variability, the larger the F-ratio, the larger the variability due to the reeds in comparison to the variability due to the repetitions (repetition error of the expert). The assessments of the expert are repeatable enough to show a significant reed effect, particularly for *ease of playing*.

A principal component analysis was conducted on the mean ratings to show the correlations between the subjective descriptors and to explain the main differences between the reeds. The first two components account for more than 87% of variance. This high percentage signifies that the reeds locate mainly in a bi-dimensional space and that interpretations of the differences between reeds can be made in this space, the loss of information being weak

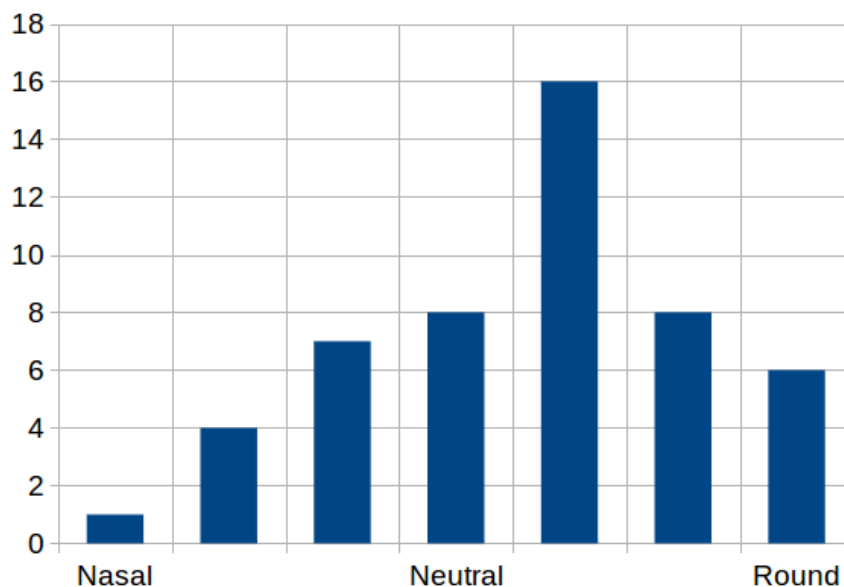


FIGURE 13: Distribution of *roundness* mean values for set 1 (50 unselected reeds)

(13%). To help the interpretation of the factorial plane, a VARIMAX rotation in the factorial plane is provided. The principle of VARIMAX is to rotate the two axis of the plane of the first two principal components in order to associate (as much as possible) each descriptor to at most one axis. After VARIMAX, the data are not represented according to the two principal components any more, but according to a new system of coordinates (D1, D2) that facilitates the interpretation. Figure 13 presents the map of the variables according to D1 and D2 (47% of variance is accounted by D1, and 40% by D2). Given the orientation of the descriptors in the plane, the first dimension is largely created by the two descriptors *ease of playing* and *brightness* which are correlated. The second dimension is largely created by the descriptor *roundness*.

4.1.2. Correlation Objective parameters /subjective descriptors

To provide an interpretation of the subjective descriptors, a one to one linear correlation between each subjective descriptor and each objective parameter is proposed. The linear coefficient of correlation is given in table 2 with the p-value of the significance test.

The most important correlations are between the *ease of playing* and the static and dynamic compliance ($R = 0.74$; $R = 0.75$).

A causality is suspected between compliance (static or dynamic) and *ease of playing*. Indeed, the physical model of the reed predicts a monotonous relationship between the compliance of the reed and the threshold pressure, which may govern the descriptor *ease of*

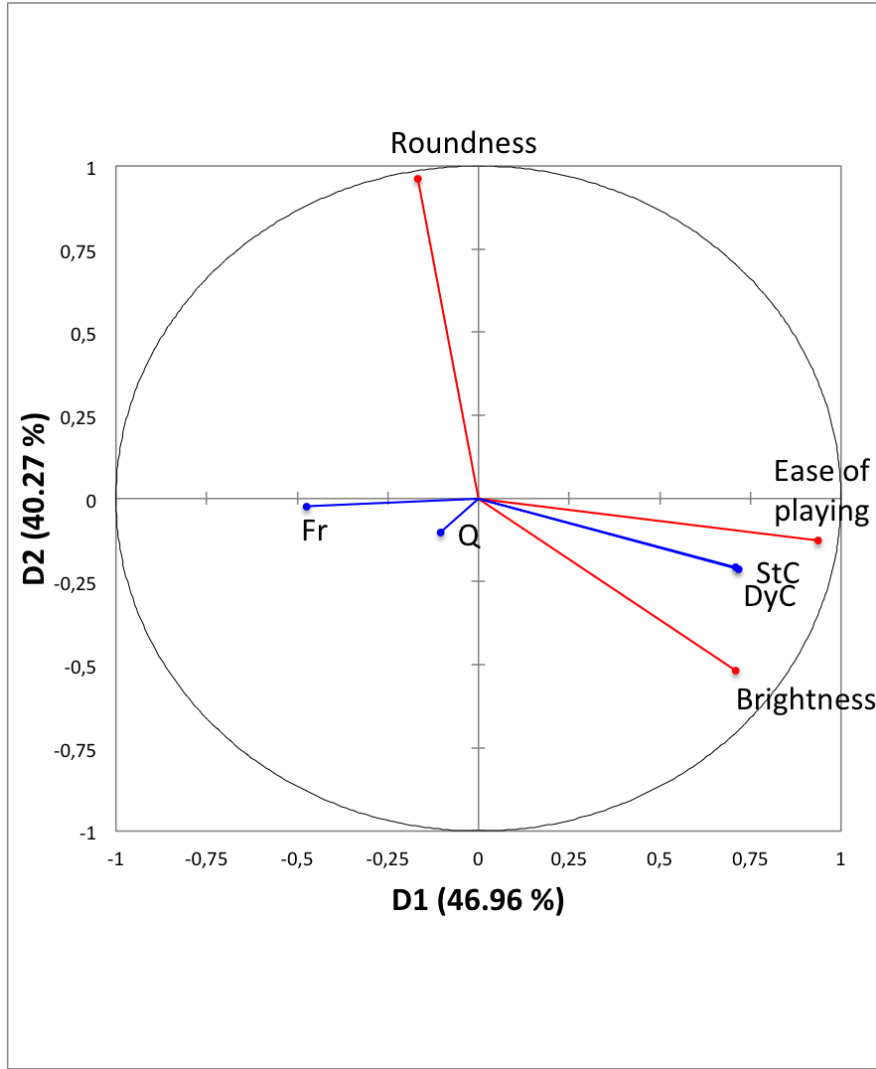


FIGURE 14: PCA of the subjective assessments (map of the variables, with VARIMAX rotation)

	<i>StC</i>	<i>DyC</i>	<i>Fr</i>	<i>Q</i>
<i>Brightness</i>	0,56 (***)	0,52 (***)	-0,28	-0,03
<i>Ease of playing</i>	0,74 (***)	0,75 (***)	-0,47 (***)	-0,08
<i>Roundness</i>	-0,35 (*)	-0,36 (*)	0,08	-0,08

* $p < 0.05$ - ** $p < 0.01$ - *** $p < 0.001$

TABLE 2: linear coefficient of correlation between the objective parameters and the subjective descriptors.

playing [27]. This result confirms the representativeness of the physical model.

Figure 15 shows the *ease of playing* versus the dynamic compliance. For all the reeds, it

shows a monotonous relation between the two variables but the difficult reeds (low DyC) show a large dispersion which might be due to the high uncertainty in the expert's rating.

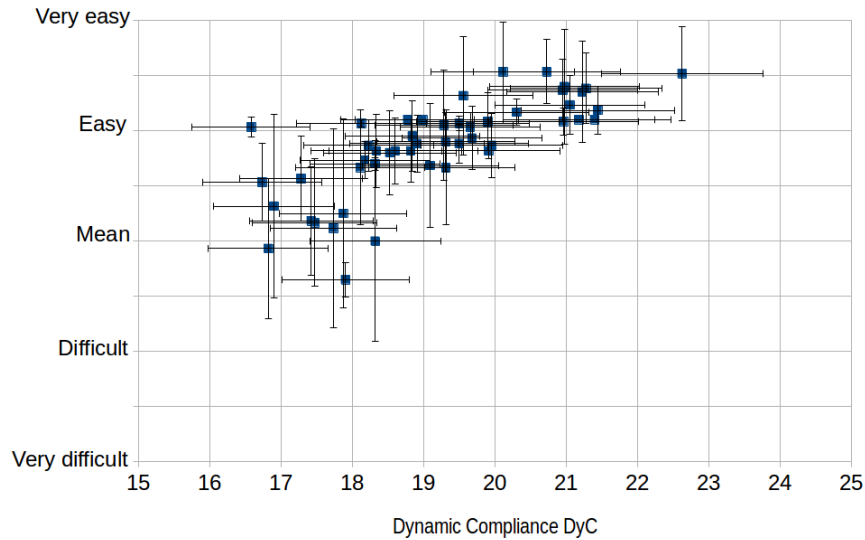


FIGURE 15: *ease of playing* for set 1 (50 unselected reeds) as a function of dynamic compliance. Plot of mean value and uncertainty as error bar.

The correlation between static and dynamic measurements shows a high correlation ($R = 0.99$) for a large range of strength (1 to 5) as shown in §3.4 and on figure 9. In practice, such a range can not be played by one musician who is using only a single strength value (3 or 3.5 usually). For the set of 50 'unselected reeds', the correlation between static and dynamic measurement is lower ($R = 0.80$). The fact that the range for static compliance is $\pm 10\%$ and that the uncertainty in dynamic compliance is $\pm 5\%$ might explain the relatively lower correlation.

Finally, as dynamic compliance and static compliance are correlated ($R \simeq 1$ for strength 1 – 5 and $R \simeq 0.8$ for strength 3.5), the dynamic compliance doesn't give additional information compared to the static compliance to predict the descriptor *ease of playing*.

For *brightness*, the correlation with the compliance (static, dynamic) is lower but still significant. Soft reeds are easy to play and bright, which can be explained by the fact the reed can beat more easily on the mouthpiece, leading to higher harmonics in the radiated sound.

For *roundness*, correlation coefficients with compliance (static, dynamic) are low but still significant, at the 5% level. The negative sign of the coefficient makes sense, a round sound

not being bright, may then be produced by a stiff reed. This result must be confirmed by further experiments.

These conclusions are also supported by observing the projection of the four objective parameters (static compliance StC , dynamic compliance DyC , resonance frequency and quality factor of the first mode Fr and Q) onto the factorial map as additional variables (figure 14).

4.2. Set 2 : 150 selected reeds

In this section, we investigate whether the expert is able to differentiate reeds with very similar static compliance. For this, reeds were selected such that the static compliance, measured using the bench described in §3.2, remains in an interval $\pm 1\%$ around the mean value ($StC = [10.1 - 10.3]$). However, the dynamic compliance range remains larger than the static compliance range ($DyC = [18 - 22]$) with a standard deviation of 0.8).

This set was made up of 150 reeds for Bb clarinet with same strength (strength = 3.5) and brand. Reeds were selected with three different cuts, named '56', 'V12' and 'Bb₂' by the makers, with 50 reeds of each cut used.

4.2.1. Subjective tests

Four descriptors were defined, in collaboration with the expert who preferred 'projection' to 'roundness' :

- *Ease of playing*, similar to set 1
- *Brightness*, similar to set 1
- *Projection*. This dimension was proposed by the expert and corresponds to the feeling that the sound propagates far away from the instrument, rated on a 5 level structured scale : very weak – weak – neutral – strong – very strong (the higher the rating, the stronger the *projection*).
- *Global quality*. This dimension is related to the overall quality of the reed, linked to the experience and the preference of the musician. It was rated on a 5-level structured scale : very bad - bad – average – good – very good.
- In addition to these descriptors, the expert had to indicate which type of reed he thought he was playing (V12, 56, or Bb₂). This information was introduced to assess the ability of the expert to recognize the reed type. Given the abilities of the expert (he is the in-house musician for the control of playing qualities of reeds in a company), no training phase was necessary to present the reeds types that he knows perfectly.

The objective was to assess the perceptual differences between this set of very similar reeds from a compliance point of view. The F-ratios of the one-way ANOVA are presented for each descriptor and each reed type in table 3.

	56	V12	Bb_2
<i>Ease of playing</i> F-ratio	3.24 (***)	4.005 (***)	6.87 (***)
<i>Brightness</i> F-ratio	1.44 (N.S.)	1.74 (*)	2.07 (**)
<i>Projection</i> F-ratio	2.09 (**)	3.56 (***)	10.8 (***)
<i>Global quality</i> F-ratio	2.48 (***)	2.16 (**)	6.42 (***)

(N.S.) $p > 0.05$ - * $p < 0.05$ - ** $p < 0.01$ - *** $p < 0.001$

TABLE 3: Results of the one-way ANOVA for each descriptor and each reed type (F-ratio).

Except for the descriptor *brightness* for reeds '56', all the effects were significant. The most important effects were for the ' Bb_2 ' reed type, and for the descriptor *ease of playing*, which obtained the most important F-ratios. The assessments of the expert are repeatable enough to show a discriminant assessment of the reeds, since they have very similar strength. In general, the most important effects were obtained for Bb_2 reeds, particularly for the descriptor *projection* (proposed by the expert). The F-ratio was smaller for reeds 56 and V12, the assessment being less reliable.

The recognition rate of the expert was very high (100% for the family 56, 96% for V12 and 99% for Bb_2), a sign of a very good ability to identify the reeds in a blindfold test.

The principal component analysis was conducted on the Bb_2 reed data to show the correlation between the subjective descriptors. Two factors were sufficient to take account for 95% of variance. So the reeds locate mainly in a bi-dimensional space and the descriptors are correlated. Figure 16 represents the map of the variables according to the two principal components F1 and F2 (F1 : 81.19% of variance, F2 : 14.55%). The first factor is largely created by the three descriptors *ease of playing*, *projection* and *global quality* which are correlated. The second factor is more difficult to interpret, given that it is created by almost all the descriptors (largely *brightness*) and given that the percentage of variance on this factor is low (14.55%). As a conclusion, the perceptual space of the reeds is highly dominated by one dimension (that can be interpreted as the general quality of the reeds). The consequence of the selection of reeds according to the static compliance (set 2) is that the perceptual differences

between the reeds become mono-dimensional. The proposed descriptors and the ratings of the expert are unable to provide a second dimension that could explain the differences between the reeds. Similar results were obtained for the reeds 56 and V12.

The factorial map (Figure 16) shows the descriptors that describe the dimensions of the perceptive space.

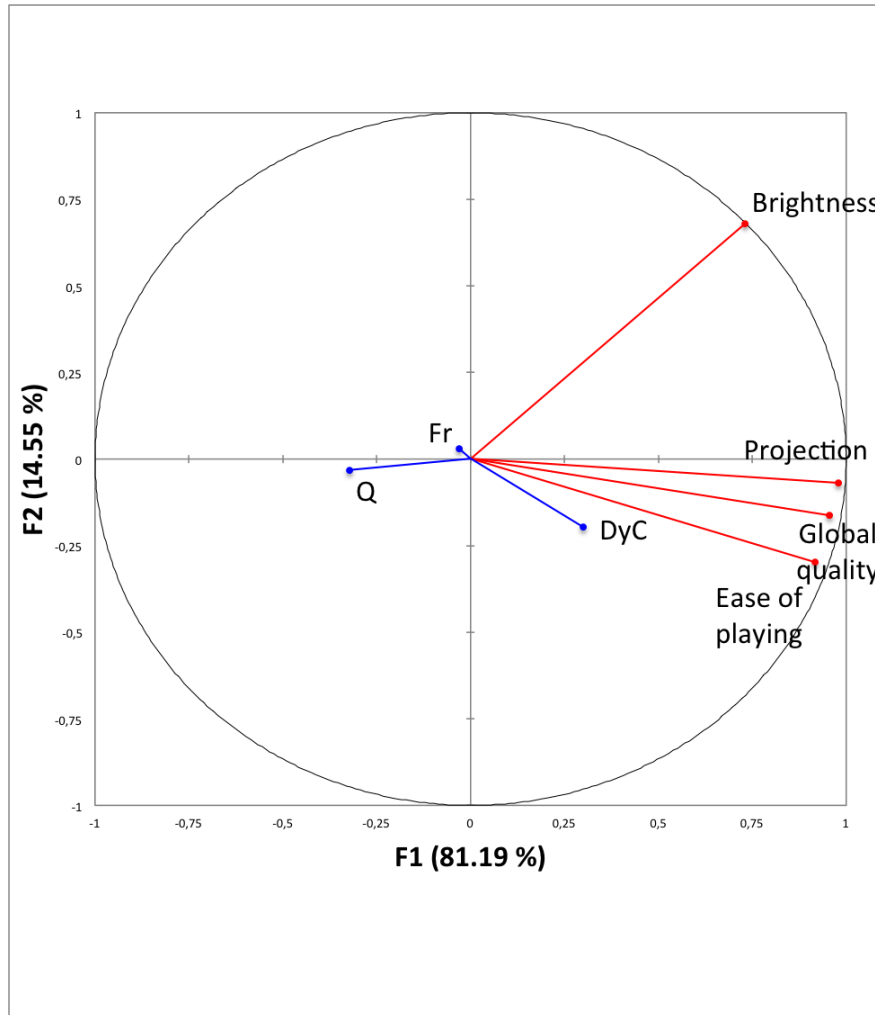


FIGURE 16: PCA of the subjective descriptors – reeds type Bb_2 (map of the variables).

4.2.2. Correlation Objective/subjective

Table 4 shows the correlation coefficient between objective parameters obtained with the VA bench and the four subjective descriptors in the case of Bb_2 reeds. It shows a significant but low correlation between *ease of playing* and compliance *DyC*, which conforms to the previous experiment and suggests that *DyC* and *StC* are not strictly equivalent.

Finally, the analysis of the correlation coefficient did not give an additional explanation about the perception of the reed behaviour. This can be explained by the fact that the reeds

were intentionally selected with a constant static compliance (which is highly correlated with the dynamic compliance). Similar results were obtained for 56 and $V12$ reeds.

	DyC	Fr	Q
<i>Brightness</i>	0,10	0,01	-0,25
<i>Projection</i>	0,27	-0,05	-0,30 (*)
<i>Ease of playing</i>	0,41 (**)	0,01	-0,23
<i>Global quality</i>	0,27	-0,07	-0,38 (**)

* $p < 0.05$ - ** $p < 0.01$ - *** $p < 0.001$

TABLE 4: Linear coefficient of correlation between the objective parameters and the subjective descriptors for reeds Bb_2 .

5. Conclusion

In this work, two sets of reeds were characterised subjectively by an expert and measured using a static bench and a vibroacoustics bench.

Results obtained with a set of 50 reeds (strength 3.5) show that the subjective tests showed significant differences between the reeds the descriptors *ease of playing*, *brightness* and *roundness*, the effect being the highest for *ease of playing* and the lowest for *roundness*. A principal component analysis shows that the perceptual space is almost bi-dimensional. The first dimension was largely created by the two descriptors *ease of playing* and *brightness* (which are correlated). The second factor is largely created by the descriptor *roundness*. Correlation between subjective indicators and objective parameters show that *ease of playing* is correlated with the static compliance and dynamic compliance of mode 1. Although the reed strength is constant, this experiment showed that the reed compliance (static or dynamic) can be used for selecting reeds according to a scale going from soft and bright reeds to hard and dark reeds.

Results obtained with a set of 150 selected reeds made from three families (56, $V12$, Bb_2) with the same static compliance (range $\pm 1\%$) showed that the expert can recognise the reed family with a recognition rate higher than 96%. The subjective tests showed significant effects of the reeds for all descriptors except for *brightness* and reeds 56. The expert perceived a larger variability for the Bb_2 reed type, and for the descriptors *ease of playing* and *projection*, that obtained the most important F-ratios in the ANOVA. However, the *ease of playing* descriptor still dominates despite the reed having the same static compliance. When the reeds are very

similar in term of static compliance (set2), the Principal Component Analysis showed that the perceptual differences between the reeds rated by the expert is almost mono-dimensional (general reed quality). Due to the very small variability of static compliance, the correlation coefficients between subjective descriptors and mechanical parameters, including higher mode properties (compliance, quality factor, frequency, symmetry), did not explain the perceptual space in this case.

Finally, this work showed that the mechanical parameters (static compliance, vibration characteristics) of the reed alone are strongly correlated with the *ease of playing* and *brightness* for reeds having the same strength. This property is already used by manufacturers to offer musicians the possibility of selecting reeds more accurately using the measurement of the static compliance. However the experiment with reeds of equal static compliance showed that the ease of playing is not fully explained by reed compliance. This suggests that the interaction between the reed and the mouthpiece lay during playing can not be ignored, particularly because the reed displacement amplitude is much higher while playing than during the measurement process with mechanical benches. So, the important conclusion of the work is that it is necessary to make measurements at high displacement corresponding to playing conditions using the measurement of important physical quantities such as mouthpiece pressure, mouth pressure and reed tip displacement.

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