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Paper superficial waviness: Conception and implementation of an industrial statistical measurement system

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Abstract

The development of proper measurement methodologies for product evaluation is a critical issue to papermakers since their customers are increasingly demanding in regard to new product development and product quality.

This paper addresses the conception of a measurement system to assess objectively and systematically paper superficial waviness in industrial practice. Such a system is based on mechanical stylus profilometry. The measurement system conception process is presented in this article, considering all of its stages: (i) gage selection and auxiliary components creation, (ii) drawing of a measurement procedure, (iii) assessment of the system capacities (through a repeatability and reproducibility (R&R) study), (iv) design of an appropriate categorical scale for paper waviness classification, and (v) validation of the classification model.

The definition of the categorical scale encompassed the sensorial and instrumental characterization of several sheets of paper. The corresponding classification model strongly relies on the quality of judgments made by a panel of experts, and therefore the definition of a *golden standard* was carefully conducted. Two distinctive methodologies were used to assess the perceptiveness of the judges regarding paper superficial waviness, and linear discriminant analysis with stepwise variable selection for dimensional reduction was then applied to build a final classification model.

The system conceived can be very helpful in the field of product design and process development, besides its obvious application to the monitoring of paper superficial quality. In fact, it can play an important role as an instrument used to define process–structure and structure–properties relationships, which may help in achieving faster product design time cycles.

Keywords: Paper superficial waviness; Measurement system; Product design; Process quality control

1. Introduction

Nowadays, pulp and paper industries face great demands to control process quality, meet product specifications, correspond to customer needs and assess their R&D activities. As a result, the development of proper measurement methodologies for product evaluation becomes a critical issue. Chemometrics data analysis tools have been extensively applied to this industrial sector, namely to handle the high dimensionality and strong collinearity present in process databases [1–3], and, more recently, to cope with the challenges raised by new measurement units producing several types of spectra [4,5], where wavelet theory has been playing an important role in the extraction of relevant predictive components spread across wavelength scales. Other applications regarding the analysis of quality features of pulp and paper products, such as pulp properties [6], paper cockling [7] and paper curl [8], have also been referred in the literature, the last two being relative to paper deformation phenomena, and therefore some-

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how related to this work. However, the quality problem addressed in this paper that of paper waviness, does have quite different underlying root causes and involves distinct paper deformation patterns.

This article addresses the conception and implementation of an industrial and statistically based paper superficial waviness measurement system. Such a measurement system was developed in close collaboration with Portucel SA (a major Portuguese pulp and paper company), and is now being used regularly at one of its industrial facilities for product design activities.

Paper surface characteristics play an important role in the final product quality, as they affect ink transfer to the sheet and hence printability [9]. Owing to technological developments in the printing industry (namely in the fields of colour and resolution) the significance of paper surface in paper quality has increased even further in recent years.

The surface or texture characterization is an important component of paper surface description. From a structural perspective, any surface (including that of paper sheet) can be seen as the overlap of three types of irregularities, form and position errors, waviness and roughness (Fig. 1), which can be distinguished by their horizontal pattern (scale).

Traditionally, paper surface texture is characterized using methods based on air leak instruments that provide a global roughness value relative to a macroscopic region of the sheet [10]. It is known that these methods, despite being very simple, are ineffective in distinguishing and characterizing the different structural scales of the surface, namely as far as the waviness phenomenon is concerned. In fact, this phenomenon is usually described through visual analysis. This type of human-based procedure is time-consuming, fairly subjective and inaccuracy prone, and therefore it is incongruous with the current demands posed by customers to papermakers regarding new product development and product quality assurance.

In this context, the present work addresses the conception and implementation of a measurement system that allows one to assess the paper superficial waviness in a quantitative, objective and systematic way. The measurement system conception process is presented considering all of its stages, ranging from gage selection to statistically based measurement model generation and validation. Thus, in the next two sections the measurement apparatus and the measurement procedure adopted are described. Then the assessment of the attributes and capabilities of the proposed system are addressed. In the following two sections the design and validation of an appropriate statistical model for paper superficial waviness classification are presented. This model was obtained employing sensorial analysis and multivariate statistical techniques. Finally, in the last section, some conclusions are drawn along with plans for future work. The practical benefits associated with the measurement system conceived and implemented are also discussed.

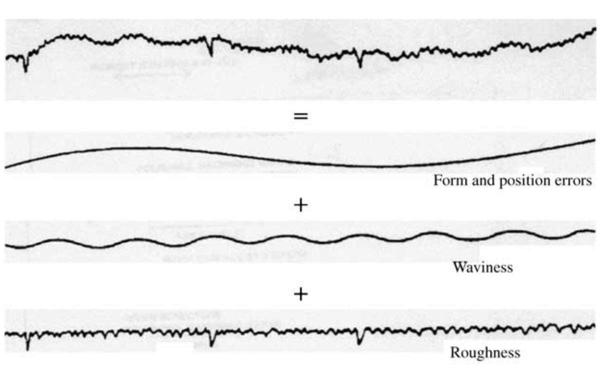

Fig. 1. Schematic representation of three paper surface structure components.

2. Measurement device

The first step of the measurement system conception process was gage selection, leading to the adoption of a mechanical stylus profilometer (Fig. 2). Stylus profilometry techniques (based on either mechanical tracing systems or optical probes) are widely used in assessing surface textures [12], and several references can be found in the literature covering this topic, namely with applications in the areas of bioengineering and machine finishing [13–16]. As far as paper is concerned, these evaluation techniques are becoming also popular, although their use in this field is not yet fully explored. In fact, some applications in the context of surface roughness assessment have been reported [9], but it is believed that the work presented in this paper represents the first attempt for describing paper long-scale surface irregularities (waviness) through stylus profilometry in real industrial environments.

The use of the gage selected in the context of paper surface assessment demanded the careful design and construction of an auxiliary component that guarantees the proper positioning of the sheet under analysis. As shown in Fig. 3, this component is basically composed by a screw (A), a flexible cramp (B) and a fixed cramp (C). Thus, the measurement device developed includes the mechanical stylus profilometer (gage) and the sheet support unit. These two elements affect the performance of the measurement system and must be considered all together when assessing its attributes and capabilities.

Fig. 2. Photograph of a mechanical stylus profilometer (available in [11]).

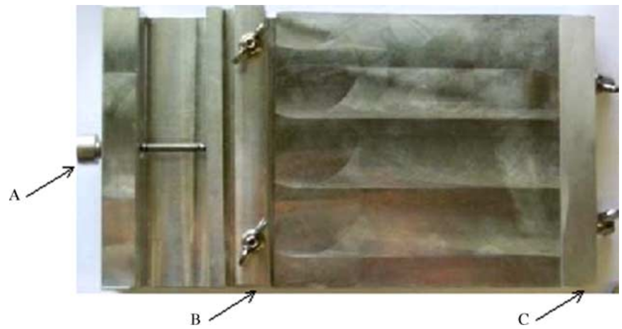

Fig. 3. Photograph of the sheet support included in the measurement device (A, screw; B, flexible clamp; C, fixed clamp).

3. Measurement procedure

The definition of a proper measurement procedure was another crucial step in the measurement system conception process. Actually, product characterization could not be reliably addressed until a systematic measurement approach was made available.

The measurement methodology was established iteratively, based upon experience and background acquired while the instrumental technique was tested and refined.

The final measurement procedure (schematized in Fig. 4) involves the following four main steps:

(i) An item dimensioned according to the sheet support unit (10 cm × 14 cm) is cut from the original paper sheet that one is intending to analyze (Fig. 4(a)). The cut is performed so that the larger dimension of the item is perpendicular to the direction of the waviness phenomenon.
(ii) The item is placed on the support unit and fixed by the two cramps. The screw is then turned providing the tension needed to guarantee paper horizontality (Fig. 4(b)). This step demands training in order to achieve a suitable position for the item.
(iii) Once the item is correctly positioned on the support, the measurement is carried out (Fig. 4(c)). The profilometer delivers several two-dimensional profiles, as well as a set of numerical parameters computed from such profiles. The former allow one to assess qualitatively superficial waviness while the later provide a quantitative and integrated description of the phenomenon. As the variation of the superficial texture characteristics within the item may be significant, the measurement procedure comprises five profiles of the surface taken with different starting-points located in non-coincident parallel lines. The final results of the measurement made over an item are then calculated by averaging the numerical parameters computed from the individual profiles recorded this way.
(iv) At last, the measurement quantitative output is introduced in the statistical categorical model, so that the waviness quality of the item can be judged and classified (Fig. 4(d)).

4. Measurement system performance assessment

When conceiving a novel measurement approach in the scope of process or product quality control, it is important to assess its performance regarding the quantification of the variables of interest. In fact, to address actual process variability, the variation due to the measurement approach (measurement device and operator) must be identified and separated from the one effectively involved in the process. In the work presented here, this kind of analysis was carried out through a repeatability and reproducibility study (R&R study) [17].

In general, an R&R study involves the evaluation of a set of items using the measurement device throughout two or more trials performed by one or more operators. Overall, this study consists of a set of experiences properly planed, whose results can be explored employing ANOVA techniques. As output, this study splits the variability within a set of measurements in three fractions: (i) the fraction that is effectively process-related, (ii) the fraction that is due to the measurement device and therefore observed when an operator measures the same item with the device several times (repeatability), and (iii) the fraction that depends on the operator and therefore is observed when several operators use the device to measure the same item (reproducibility). Additionally, under particular circumstances, variation within the same item is identified as a fourth variability source.

The R&R study of the superficial waviness measurement approach is briefly described below in terms of the adopted experimental procedure and main results obtained.

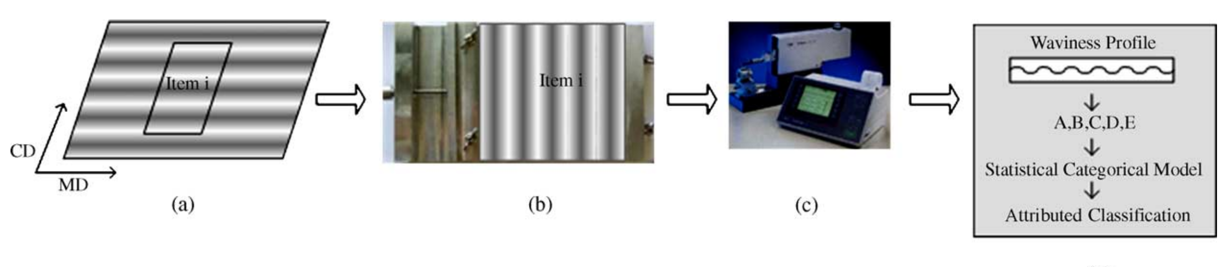

Fig. 4. Schematic representation of the measurement procedure: (a) direction of the waviness phenomenon; (b) placement of an item in the sheet support; (c) acquisition of the waviness profile; (d) classification task.

5. Experimental procedure

This study involved two major stages:

(i) Two operators characterized the superficial texture of eight paper items throughout two trials. Five measurement starting-points for each item were kept fixed between trials in order to avoid variation within the same item. Data obtained at this stage provided values of repeatability and reproducibility of the measurement device.
(ii) A similar experimental procedure was adopted, except for the fact that measurement starting-points in each item were not maintained between trials. Data produced in this stage, along with the previous results, allowed estimating the waviness variability within the same item.

6. Results and discussion

Several numerical parameters delivered by the profilometer were considered in the R&R study. Table 1 presents results relative to the five parameters that will be included in the classification model (detailed in Section 7). *A*, *B*, *C* and *E* describe the waviness profile in terms of its amplitude, while *D* is an integral metric that addresses the asymmetry of the profile (these parameters are defined according to reference [18]). The results are shown in terms of the percentage of total variability in the set of measurements associated with each component: $(\text{R\&R})^{\%}$ represents the variance fraction due to the combined effects of measurement device and operator; $(\delta^2_{\text{item}})^{\%}$expresses the variance fraction explained by variation within each item.

Usually, a measurement approach is considered acceptable from a precision point of view when a value of $(\text{R\&R})^{\%}$ smaller than 30% is found [17]. Hence Table 1 shows that some improvement actions are still needed in order to enhance the system's R&R performance, namely through an increase in the measurement length.

The results obtained $(\delta^2_{\text{item}})^{\%}$ also show that the effect of the items' internal texture variation is negligible in the context of the total variability for a set of measurements. This fact can be due to the following reasons.

According to the measurement procedure described above, each measurement consists of five profiles started at different points of the paper sheet surface. This practice minimizes the effect of surface internal variation in the final measurement results.

Waviness is a large-scale phenomenon (10^{-2} m), and hence its heterogeneity is smaller than that verified in the case of superficial characteristics occurring at a fine scale (10^{-3} m), such as roughness.

Table 1
R&R study results

Waviness metrics	$(\text{R\&R})^{\%}$ (%)	$(\delta^2_{\text{item}})^{\%}$
A	14.0	7.5
B	52.7	0.2
C	42.2	0.0
D	54.6	18.8
E	53.7	0.0

7. Categorical scale design

The last step in the measurement system development comprised the definition of a statistical model that allows one to judge the quality of the item analyzed using the measurement device and procedure.

The usual approach adopted to appraise paper waviness is to rely on sensorial analysis results obtained from an operator in charge of attributing a certain grade (e.g. excellent, good, and bad) to each item. At this stage of the measurement system development, the goal was to derive a statistical classification model consistent with such visual inspection results, which should also be reproducible and more suitable for routine operation.

The definition of a *golden standard*, or, in other words, the construction of a standard that represents the opinion of the panel with a good degree of agreement between the judges was a critical step to support the construction of the classification model. Model building comprises the following three phases: (i) definition of the *golden standard*, (ii) comparison with measurement device results, and (iii) selection of the variables to be included in the final classification model, and corresponding parameters estimation.

8. Experimental procedure

The experimental work began through the careful choice of a set of paper items, representative of several waviness quality classes. Such items were then analyzed according to the measurement procedure previously described. In this case, all the 13 waviness parameters provided by the profilometer were saved for further analysis.

The same items were also evaluated by a panel of experts, whose selection took into account their personal acquaintance with paper waviness assessment.

Sensorial analysis was performed after explaining to each judge what the goal was, without providing any a priori standard to him or her.

Each of the 11 judges was requested to distribute 30 items, assuming a certain number of quality classes that he/she believes to be relevant and distinguishable, where class *N* corresponds to the inexistence of waviness and class 1 represents the class were the phenomenon is more perceptible. The ensuing table of classifications reflected a high level of disagreement concerning the number of classes discerned. The low degree of correlation between judges indicated that there were no strong enough relationships between the classifications performed by the judges that divided the items amongst a few classes (2 or 3) and those that considered more categorical values (5 or 6).

To overcome this problem, in a second round eight panel members were requested to classify 34 items according to a prefixed number of four classes. Since there were members in the panel who had no sensitiveness to distinguish four different classes of waviness, they were at this stage removed from the panel.

With the above modifications, at this second round high degrees of correlation were observed between the several judges, and therefore a more formal evaluation of the statistical quality of their agreement was found to be appropriate.

9. Results and discussion

To quantify the degree of agreement amongst the several panel judges, two distinctive approaches were followed: (i) an empirical method based upon the calculation of the observation frequencies and (ii) a test of hypothesis based upon the Kappa statistic. Both approaches are briefly described in the following paragraphs.

Table 2 provides the basic nomenclature required to follow the definitions of the empirical parameters for the first methodology. The observation frequency n_{ij} represents the number of votes performed by the panel for each item i in class j ($i = 1,\ldots, N$; N, the total number of items, in the present case, is of 34; $j = 1, \ldots, M$; M is the total number of classes, 4; $k = 1, \ldots, K$, where K is the total number of judges that constitute the panel, 8). The standard classification for sample i, P_i, is defined as the class j corresponding to the highest value of n_{ij} associated to item i. The attribution of a standard class is not as simple as it might seem since in several occasions the number of votes for two different classes was found to be similar. Therefore, the procedure that was followed to establish the standard class P_i involves the minimization of the total deviation of the panel relatively to the standard. Total deviation, D_t, is the mean value of the deviation parameters, D_k, for the panel of experts:

$$D_t = \frac{\sum_{k=1}^{K} |D_k|}{K} \quad (1)$$

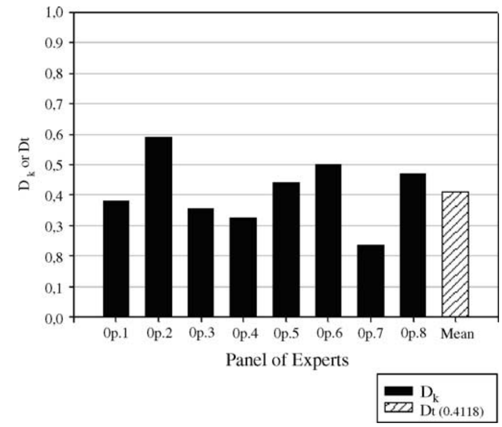

Fig. 5. Total and partial deviations relative to the *golden standard* based on four categories.

where K is the total number of judges that compose the panel, and D_k is the vector with the partial deviations of each judge k at each entry, determined by the following equation:

$$D_k = \frac{\sum_{i=1}^{N} |D_{i,k}|}{N} \quad (2)$$

Thus, D_k is given by the sum of the deviations in the classifications made judge k, for all items ($D_{i,k}$, Eq. (3)) divided by the total number of items, N:

$$D_{i,k} = |P_i - a_{i,k}| \quad (3)$$

The calculation of matrix $D_{i,k}$ is based on the matrix of classifications made by each judge k to each item i, $a_{i,k}$, and the standard classification vector P_i. In cases of doubt between two classes with similar observation frequencies, standard P_i was chosen as the class that minimizes D_t.

Fig. 5 summarizes the total and partial deviations calculated for a *golden standard* adopted to discriminate between four different categories of waviness. One can see that there are operators lacking some training regarding the assessment of this phenomenon, who are associated with higher values for D_k, resulting in higher contributions to the overall (total) deviation, D_t.The second methodology adopted in order to quantify the degree of agreement amongst the several panel judges, based upon the Kappa statistic (K) [19], brings an interesting point related with the probability of chance associated with classification. The K value is specified as the ratio

Table 2
Finding the golden standard based on the observation frequencies

Items	Judges						Classes						Standard
	1	2	...	k	...	K	1	2	...	j	...	M	
1	$a_{1,1}$	$a_{1,2}$	...	$a_{1,k}$	...	$a_{1,K}$	$n_{1,1}$	$n_{1,2}$	...	$n_{1,j}$	...	...	P_1
2	$a_{2,1}$	$a_{2,2}$	...	$a_{2,k}$	...	$a_{2,K}$	$n_{2,1}$	$n_{2,2}$	...	$n_{2,j}$	...	...	P_2
...	...	...	...	...	...	...	...	...	...	...	...	...	...
I	$a_{i,1}$	$a_{i,2}$	...	$a_{i,k}$	...	$a_{i,K}$	$n_{i,1}$	$n_{i,2}$	...	$n_{1,j}$	...	$n_{1,M}$	P_i
...	...	...	...	...	...	...	...	...	...	...	...	...	...
N	$a_{N,1}$	$a_{N,2}$	...	$a_{N,k}$	...	$a_{N,K}$	$n_{N,1}$	$n_{N,2}$	...	$n_{N,J}$	...	$n_{N,M}$	P_N

Table 3
Strength of agreement of the panel given by Kappa statistic [20]

Kappa statistic	Strength of agreement
<0.00	Poor
0.00–0.20	Slight
0.21–0.40	Fair
0.41–0.60	Moderate
0.61–0.80	Substantial
0.81–1.00	Almost perfect

between the probability of agreement of the panel, $P(A)$, and the maximum probability possible to achieve, taking into account the probability associated with chance, i.e., the probability of attributing the correct classification by chance, $P(E)$:

$$K = \frac{P(A) - P(E)}{1 - P(E)} \quad (4)$$

According to the previous equation, $K < 0$ is obtained when there is no agreement between the members of the panel, and $K = 1$ corresponds to the maximum possible agreement in the panel. A plausible scale to perform an assessment of the strength of agreement within the panel is therefore the one illustrated in Table 3 [20]. The evaluation of the panel's quality was measured using parameter K, leading to a score of 0.36, which indicates that there is a fair strength of panel's agreement.

Based on these results, the possibility of building a *golden standard* with just three different categories was also considered. The opinions were thus grouped according to this alternative problem formulation, and the associated values of D_k and D_t are presented in Fig. 6. The value of Kappa calculated for a *golden standard* based on three categories is 0.52, indicating a substantial improvement over the agreement level obtained within the members of the panel.

Table 4
Classification matrix of the model used to discriminate waviness in three categories (training results)

Predicted classifications	Observed classifications			
	Percentage correct (%)	G_1	G_2	G_3
G_1	66.67	6	2	1
G_2	100.00	0	12	0
G_3	100.00	0	0	8
Total	89.66	6	14	9

Using this option as the final *golden standard*, the conception of a statistical classification model able to explain and predict the sensorial perception of the waviness phenomena was then considered. To achieve that goal, general discriminant analysis (GDA) [21] was used along with a stepwise variable selection procedure, to identify the variables (amongst the 13 different waviness parameters provided by the measurement device) that mostly discriminate between classes. To initiate the model building, a data table gathering all the variables considered in the study and the standard opinion of the panel (at first with both three and four different waviness classes) was constructed. Using such a table, GDA was used to find the functions, given by linear combinations of independent variables, which mostly discriminate between the classes. The resulting set of final classification models do achieve a correct percentage of classifications of 75.53% with four waviness categories and 89.66% of correct classifications for three separate quality classes. Therefore, once again the results drove to the adoption of three classes as the most suitable and meaningful number of waviness quality categories. Eq. (5) describe the classification functions reached this way, while Table 4 reports the global percentages of correct classifications associated with this model:

$$\begin{cases} G_1 = 11.58 \times A + 81.99 \times B - 2.26 \times C + 1036.76 \times D - 5.72 \times E - 1821.80 \\ G_2 = 11.55 \times A + 81.72 \times B - 2.75 \times C + 1044.25 \times D - 4.58 \times E - 1839.42 \\ G_3 = 10.80 \times A + 76.42 \times B - 2.18 \times C + 1020.24 \times D - 5.02 \times E - 1733.26 \end{cases} \quad (5)$$

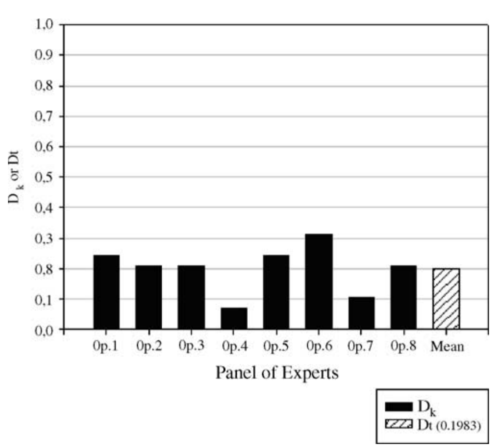

Fig. 6. Total and partial deviations relative to the *golden standard* based on three categories.

10. Categorical scale validation

In order to validate the classification model, a new data set comprising 31 items was submitted to the same experimental procedure adopted for building it.

To perform the validation of the model, two judges were asked to classify the items by sensorial analysis. However, this sensorial analysis was not performed by direct observation of the samples but by looking to the waviness profiles, thus representing a major difference between the categorical scale design procedure and the validation one. The inclusion of the waviness parameters in the classification model (Eq. (5)) led to the identification of the items category (the category is defined by the index of the greatest G_i value ($i = 1$, 2, and 3)). Table 5 summarizes the results obtained, namely the

Table 5
Classification matrix obtained for model validation (test results)

Predicted classifications	Observed classifications			
	Percentage correct (%)	G_1	G_2	G_3
G_1	75.00	6	1	
G_2	84.62	2	11	4
G_3	85.71		1	6
Total	74.19	8	13	10

percentage of correct classifications achieved in this validation stage.

As expected, the percentage of correct classifications for the test set is now lower (74.19%) than the one obtained for the training data (89.66%). The observed differences can be justified not only by the fact that they derive from a new set of items, but also by the combined effects of the distinct procedure used for sensorial analysis and the utilization of a panel constituted by only two judges, instead of the eight used in building the classification model. However, the performance achieved under these adverse circumstances still provides support for using this methodology in practice, especially if the difficulty involved in reaching total agreements in the sensorial analysis made over the same samples is considered.

11. Concluding remarks

The development of proper measurement methodologies for product evaluation is a critical issue to papermakers since their customers are increasingly demanding with regard to new product development and product quality. Paper superficial texture plays an important role in product performance, but its characterization is still limited, particularly as far as waviness description and measurement are concerned.

This work addressed the conception of a measurement system to assess objectively and systematically paper superficial waviness. The system is based upon mechanical stylus profilometry, and, as far as the authors are aware, it represents the first attempt to describe paper long-scale surface irregularities through this approach in industrial settings. Although paper is a soft and easily compressed material, the mechanical profilometry technique was found to be suitable to support a measurement system.

The measurement system conception process was presented, considering all of its major stages and results: (i) gage selection and auxiliary components creation, (ii) drawing of a measurement procedure, (iii) assessment of the attributes and capabilities of the system, (iv) design and test of an appropriate statistical categorical model for paper waviness classification, and (v) validation of the classification model.

As future work, the authors are also planning to assess the potential of principal components analysis (PCA) and Fisher discriminant analysis (FDA) as alternatives to stepwise variable selection for addressing the preliminary task of dimension reduction in the classification procedure. Possible improvements of the measurement system regarding its R&R performance will also be considered.

The system conceived can be very helpful in the field of product design and process development, besides its obvious application to the monitoring of paper superficial quality. It allows one to establish a reliable relationship between paper user's perception of waviness and associated quantitative measurement results. Therefore, it can play an important role in the definition of proper process–structure and structure–properties relationships, which may in their own help one to achieve faster product design time cycles.

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