Journal of the American Society of Questioned Document Examiners, Inc.
Volume 25, Number 2, December 2023

Fast Fourier Transformation (FFT) for Paper Image Transmission as a Tool for Identification and Differentiation—Method Validation

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The aim of this paper is to validate the paper differentiation method using Fast Fourier Transform (FFT). This method allows for visualization of a specific mesh pattern left by the production line machines during paper manufacturing. With this method it is possible to determine whether two compared sheets originate from the same source (the manufacturer), or not (from different batches of the same product or from different manufacturers). During the validation process, which aimed to confirm the method's effectiveness and identify its limitations, a total of over 2500 comparisons were made of FFT paper samples. The samples were obtained from sheets of paper from the same manufacturer, as well as from different sources. Two algorithms were used for obtaining and comparing FFTs during the research. The obtained results indicated the high efficiency of the Fast Fourier Transform used, in both confirming and refuting the common origin of the compared sheets of paper.

Document examination, paper comparison, Fast Fourier Transform (FFT)

Introduction

Providing an answer to the question of whether sheets or fragments of evidence paper have originated from the same source (such as the same ream of paper, or the same batch of the product) is a task that is frequently entrusted to experts in the field of forensic document examinations [1-3]. Basic, non-destructive paper analysis is usually carried out by determining the paper's dimensions, thickness and grammage. Analysis also includes observation of the paper's physical properties, such as color, optical features revealed under ultraviolet and near- infrared, surface structures visible using oblique light microscopy, the location and color of prints applied during the production process, and the presence of specific features such as watermarks and security threads [4-6]. The obvious advantage of this type of analysis of paper properties, besides providing important forensic information, is that there is no physical interference with the examined paper. However, non-destructive paper analysis can provide for only small distinctions and is burdened with a certain risk related to the effect of external factors having already altered the paper's appearance, such as sunlight and high temperature [7-9]. Therefore, if paper samples originate from the same source, such as fragments of a single sheet, notebook, or ream; and have been stored separately under different conditions, then non-destructive paper analysis can lead to erroneous conclusions. Instrumental methods, such as Raman spectroscopy [9-10], infrared spectroscopy [10-13], gas chromatography coupled with mass spectrometry (GC-MS) [14], or elemental analysis methods [10, 12-13, 15-16], have not shown to be sufficiently effective in distinguishing paper produced by different manufacturers because the composition of the paper samples is too similar, as a result of standardized production methods.

One part of the paper manufacturing process is the removal of water from wet pulp. Each of the multiple machines that is used in the process interferes with the surface of the manufactured paper, imprinting traces upon it. Consequently, the entire combination of machines used in a given factory leaves behind patterns which differ on both the front and reverse of the paper. The Fast

Fourier Transform (FFT) algorithm then enables conversion of a scanned image of paper in transmission mode, from the spatial domain into the frequency domain. As a result, a FFT transform (power spectrum) is obtained. On the spectrum, bright spots indicate the properties of the component waves of a given image, such as their orientation, length, and amplitude [17-18] (Fig. 1).

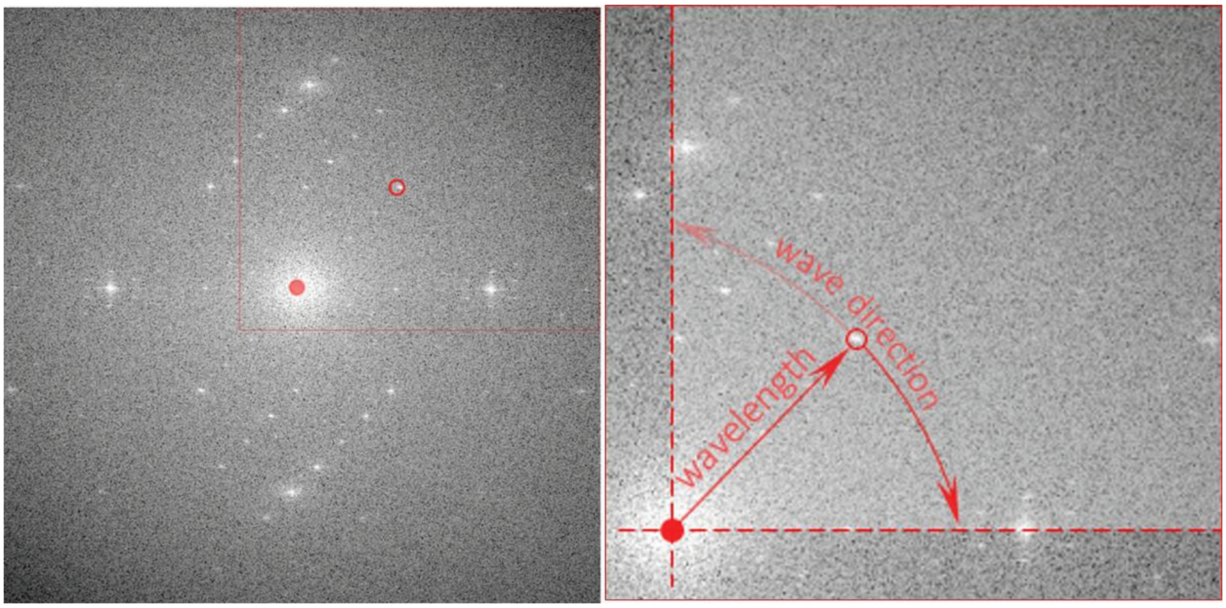

Fig. 1. Example of an FFT of a single sample of paper.

In 2002, a Japanese team of scientists used the FFT algorithm to differentiate samples of handmade paper, office paper, and newspaper [18]. The method that they used did not allow for discrimination between all combinations of pairs of twelve sheets of office paper from different brands. This was explained with the supposition that one papermaker could produce a product that was then sold under different trade names. Following their work, C. Berger [19] analyzed 25 sheets of office paper and confirmed that the same method does allow for the differentiation of paper originating from different sources, but at the same time Berger also stipulated that the presented work was only a technical, forensic validation, and that the number of tested samples was not suitable for the purposes of evidence evaluation. However, Berger did not determine whether it is possible to unambiguously establish that two compared sheets of paper come from the same source (for example, whether from a single ream of paper or from different reams of the same type, produced by the same papermaker). W. Rowe and R. Haldar, on the other hand, proved in 2021 that higher temperatures and a printing process, during which the toner is thermally fixed on the paper, does not affect the resulting paper's FFTs [20]. The FFT method was also used to differentiate between the paper-based kraft tapes that are available in Japan [21].

The authors mentioned above focused primarily on the possibility of differentiating paper samples using the FFT method. However, they did not present analyses indicating whether it is possible that this type of examination could lead to an erroneous conclusion. That is, did the two different sheets of paper originate from the same source, or to false differentiation of two sheets that originated from the same manufacturer, thus giving a false positive or false negative.

Materials and methods

85 sheets of A4 paper were collected for the research, including 75 of known origin (50 sheets of paper from two reams of Maestro Extra, 25 sheets from one ream of Xerox Premier paper), as well as 10 sheets of unknown origin that differed in grammage, color, and lines (Table 1). 971 scans with dimensions of 5 cm × 5 cm at a resolution of 2,400 dpi were made of the front and reverse sides of all the paper using an Epson Perfection V850 Pro scanner, which allows for scanning in transmitted light.

Table 1. Manufacturer, brand name, grammage, batch number of the product, and sample numbers.

Manufacturer	**Brand name, grammage and batch of the product**	**Sample numbers**
Maestro	Extra, 80 g/m^2, batch No. 9457A80S	A1_1 – A1_25
Maestro	Extra, 80 g/m^2, batch No. 9457A80S	A2_1 – A2_25
Xerox	Premier, 80 g/m^2, batch No. 003R98760	B1_1 – B1_25
NN	unknown	C1_1 – C1_10

The images obtained from the paper samples were transformed using two Fast Fourier Transform (FFT) algorithms. The first algorithm was the FFT filter designed by A. V. Chirokov, which we implemented in Adobe Photoshop [22]. The second algorithm was the ImageJ-based algorithm. The most important information in the obtained FFTs is represented by bright spots located around the brightest center part, and consists of repetitive image elements, including the grid imprinted on the paper. Bright spots are qualified as significant if the white pixel, or group of pixels representing them in the lower half of the FFTs, have their own equivalent both horizontally and vertically inverted on the upper half of the FFTs, and vice versa. As such, to facilitate the comparison of the two transforms, the bright spots were visualized graphically and then transformed into black points on a white background, forming characteristic points. This resulted in a loss of information about the intensity of the bright spots; however, this information does not play a role in sample differentiation. Using the FFT filter in Adobe Photoshop requires manual visualization and counting of the number of characteristic points, and then superimposition of the two visualizations to finally determine the correlation between the two compared paper samples. In comparison, ImageJ can automate visualization of FFTs by using a macro, the input element for which is a scan of the paper sample in transmitted light. This results in a visualization and count of the characteristic points (Fig. 2).

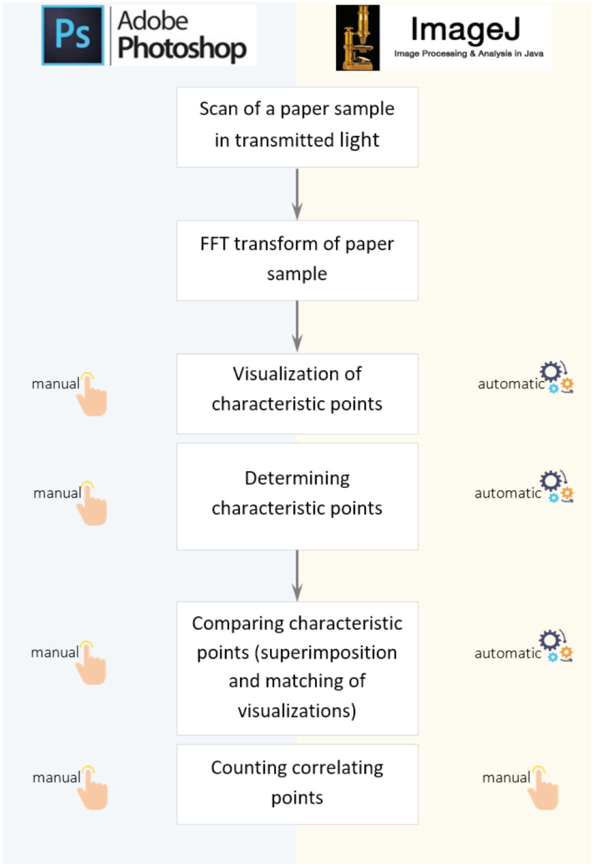

Fig. 2. Process flow of the two methods.

In the next step, the FFT transforms obtained from the paper were compared. Figure 3 presents a comparison of the two samples.

In order to assess whether the two FFTs are the same, the correlation parameter of the two samples (Z_{xy}) was calculated. For the purposes of this research, the correlation parameter was defined as the number of characteristic points that correlate (P_{xy}) between the two superimposed visualizations of the FFT samples, in relation to a transform sample with a lower number of correlations (Fig. 4).

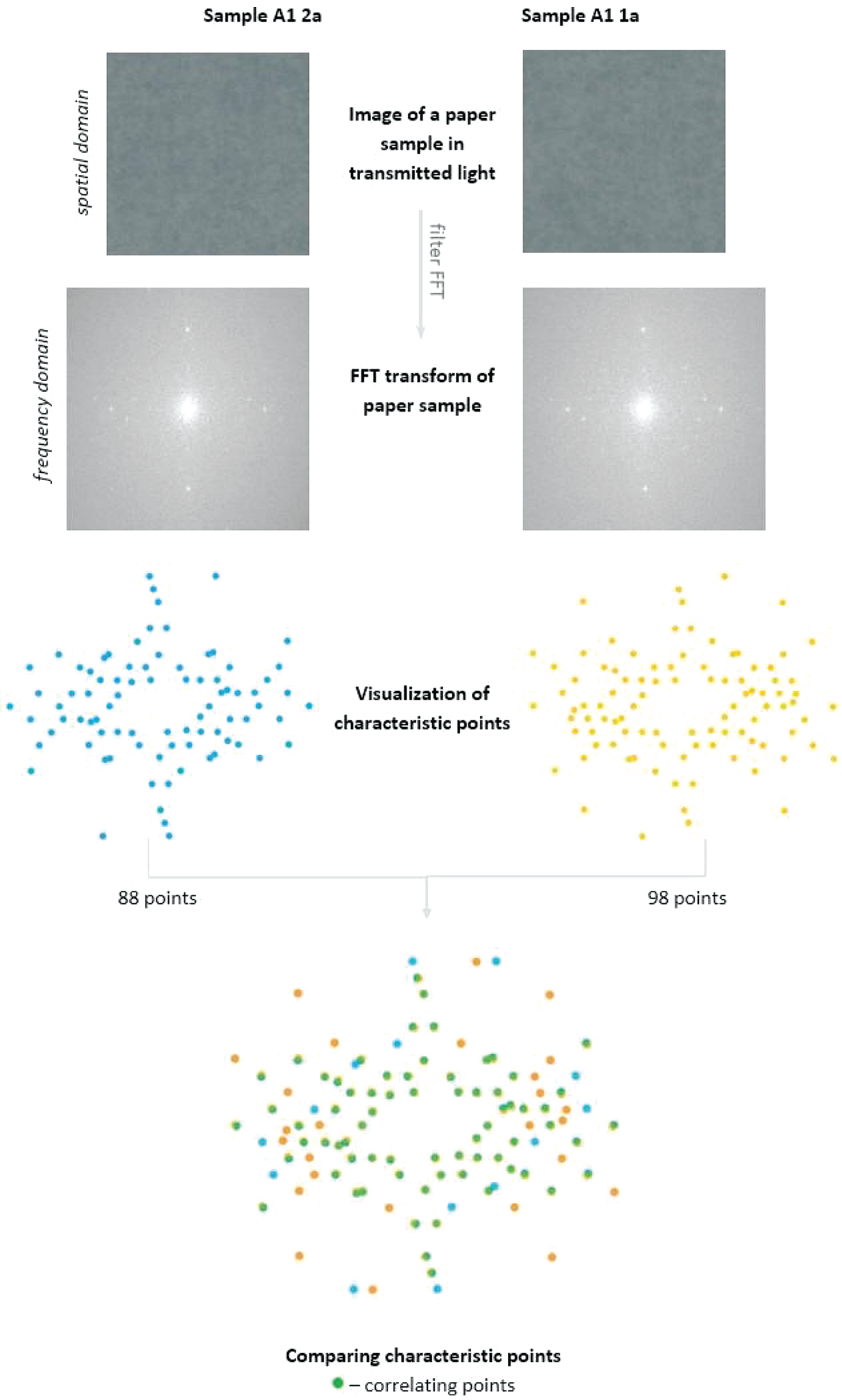

Fig. 3. Comparison of the two paper samples made using a Fast Fourier Transform (FFT).

$$Z_{xy} = \frac{P_{xy}}{P_x}, \; where \; P_x < P_y$$

Z_{xy} – two sample correlation
P_{xy} – number of correlating characteristic points
P_x – number of characteristic points on the visualization of the FFT for sample x
P_y – number of characteristic points on the visualization of the FFT for sample y

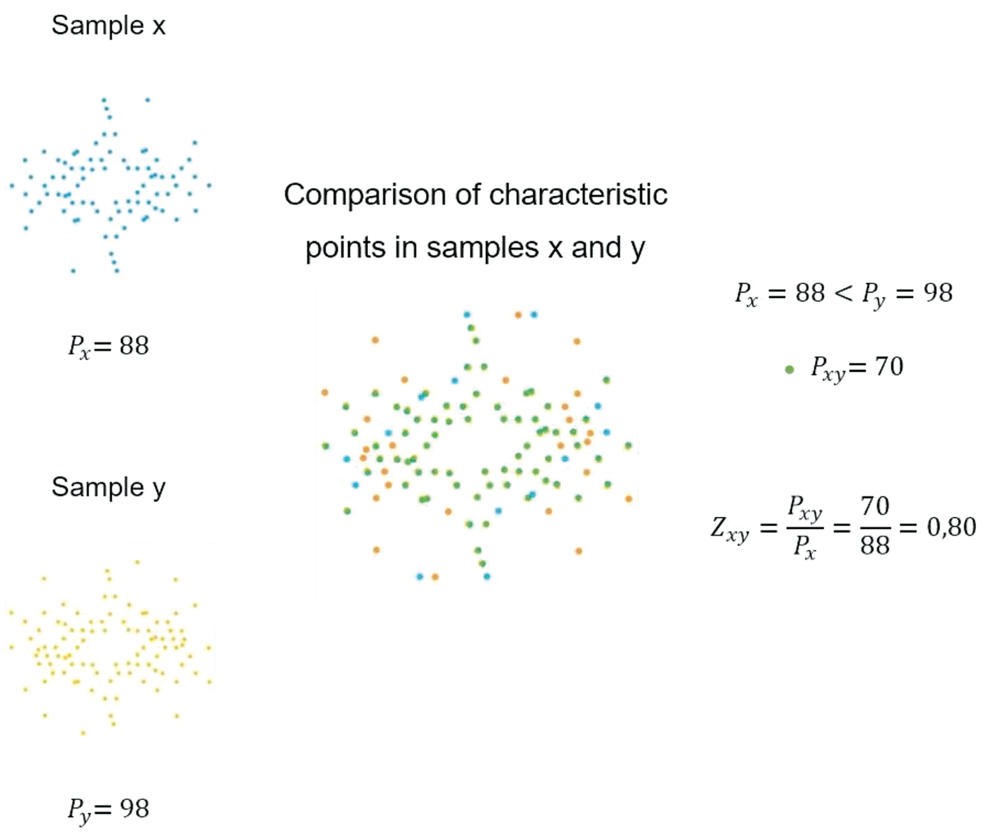

Fig. 4. Calculation of the samples' correlation (Z_{xy}).

Results

Analysis of the effect of paper orientation on the result

The first stage in the preparation of the FFTs is the process of scanning a sheet of paper in transmitted light. Therefore, to begin with, we determined whether the orientation of the sheet in relation to the scanner could affect the results. For this purpose, comparisons of the FFTs were made between the sample scans of one sheet (intra-source), which were obtained in a different orientation in relation to th scanner plate (Fig. 5). Samples from the front and reverse sides of 25 sheets from the ream of paper marked A1 1-25 and the algorithm in ImageJ were used to make the FFT for the research.

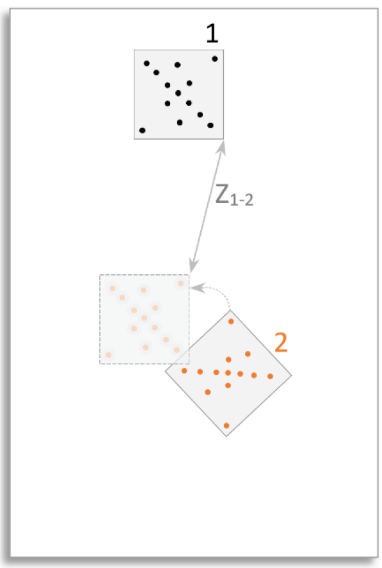

Fig. 5. Comparison of samples scanned in different orientations

This resulted in 158 comparisons for which the lowest correlation obtained was 0.75, and for 19 comparisons 1.00. Additionally, the mean correlation (0.90) and the median (0.90) were very high (Fig. 6). On this basis, it was assumed that the orientation of the paper in relation to the scanner, while maintaining the same resolution and size of the images (samples), does not have an impact on subsequent comparisons and does not affect the quality of the FFTs.

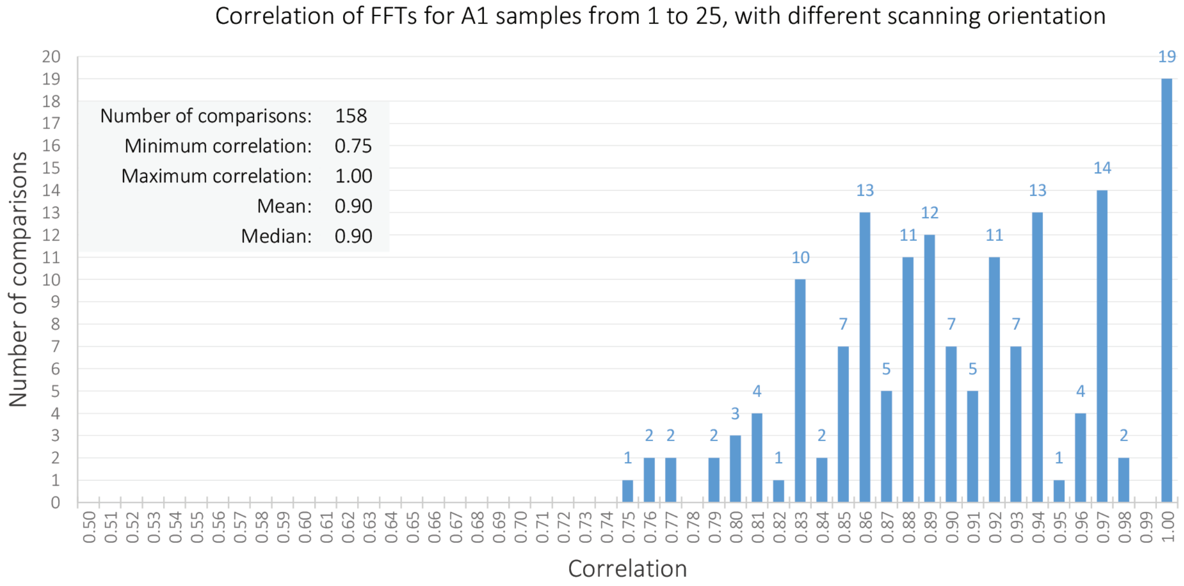

Fig. 6. Correlation of FFT samples obtained from sheets scanned with alternating orientation.

Intra-object variability analysis. Comparison of different source samples

Subsequently, pairs of transforms were compiled from the front and reverse sides of the same sheet of paper (Fig. 7), to determine whether and how the correlation range changes among samples from the same, single source. Notably, the FFTs obtained from the front and reverse of the paper differ significantly from each other, with the correlation between samples from the front and reverse sides of the same sheet being 0.00, or very close to 0.00. Therefore, such comparisons were not carried out. To obtain the FFTs and the subsequent comparison of the same samples, both the ImageJ-based 'automatic' algorithm, and the Adobe Photoshop- based 'manual' Fast Fourier Transform algorithms were used. Comparisons were carried out on paper samples marked A1_12-25 and C1_1-10.

From the 1,164 comparisons made, it was found that the correlation of two FFTs obtained from intra-source samples was very often 1.00, which means that they fully correlate. However, the lowest correlation level was 0.50, which indicated that only half of the characteristic points of the two FFTs were in the same position (Table 2).

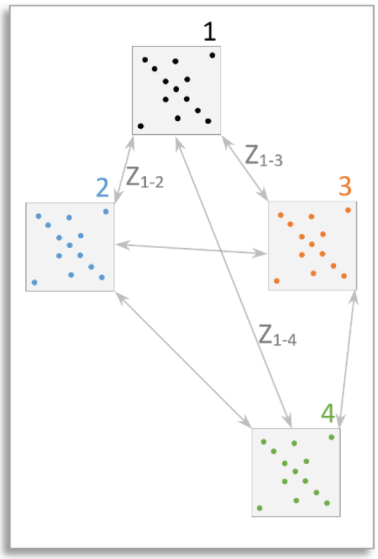

Fig. 7. Comparison of intra-source (within-sheet) samples.

Table 2. Intra-source correlation obtained when analyzing FFTs using different algorithms.

	A1 – ImageJ	A1 – Adobe Photoshop	C – ImageJ	C – Adobe Photoshop
Number of comparisons	474	285	205	200
Minimum correlation	0.73	0.68	0.50	0.60
Maximum correlation	1.00	1.00	1.00	1.00

What is equally important is that the results obtained with the use of both transformation algorithms are comparable, both in terms of the correlation between samples from the same side of single sheets of paper (the intra-source correlation), as well as the average intra-source correlation obtained within the same type of samples, whether A1 or C (Fig. 8–11).

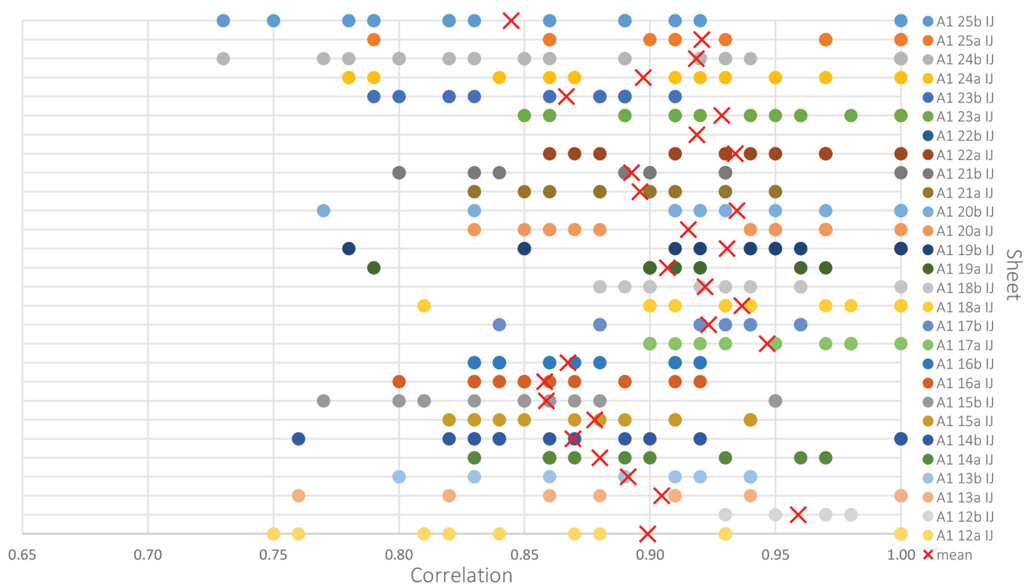

Fig. 8. Correlation ranges for comparisons of intra-source transforms (A1_12-25), using ImageJ.

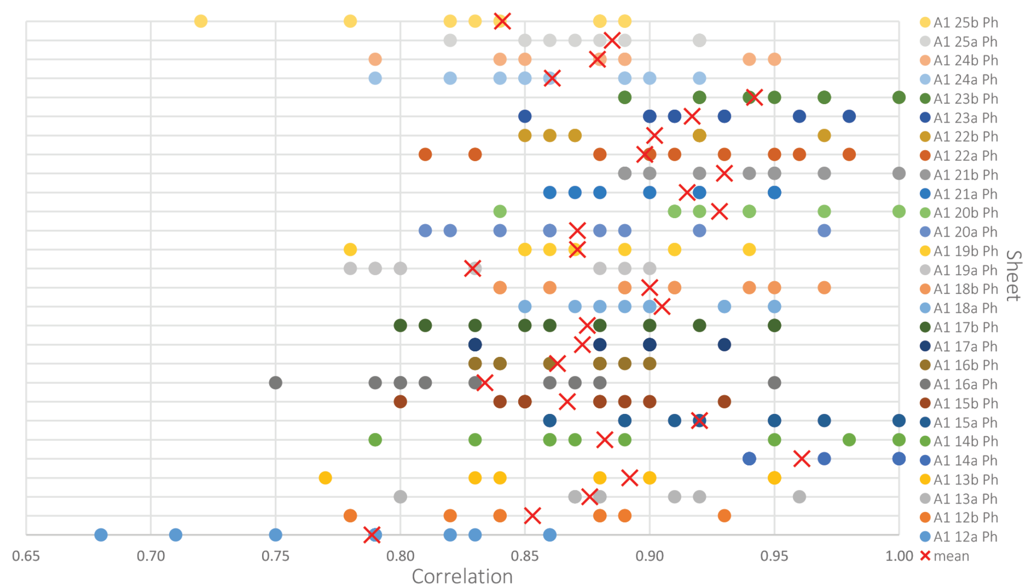

Fig. 9. Correlation ranges for comparisons of intra-source transforms (A1_12-25), using Adobe Photoshop.

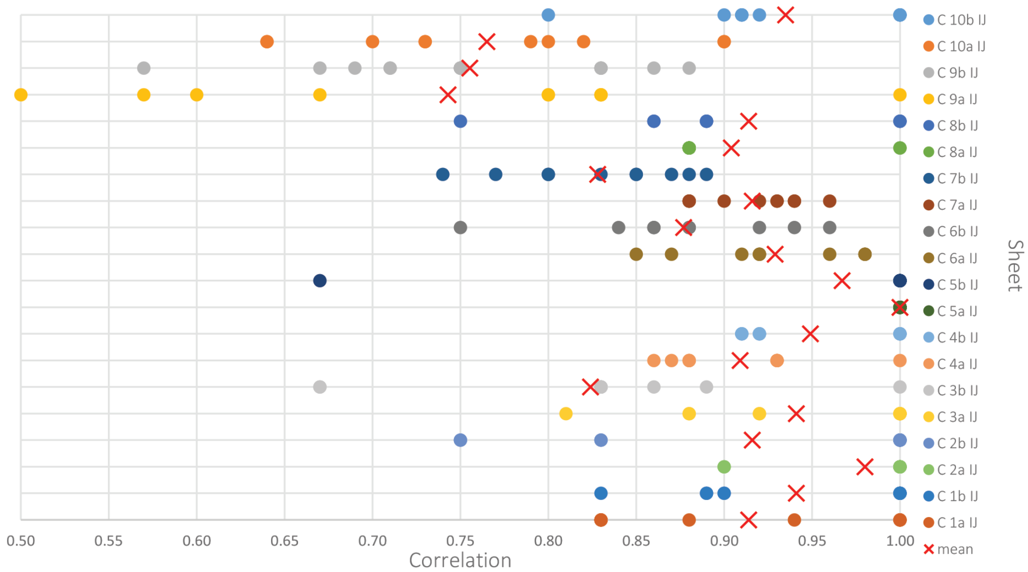

Fig. 10. Correlation ranges for comparisons of intra-source transforms (C1_1-10), using ImageJ.

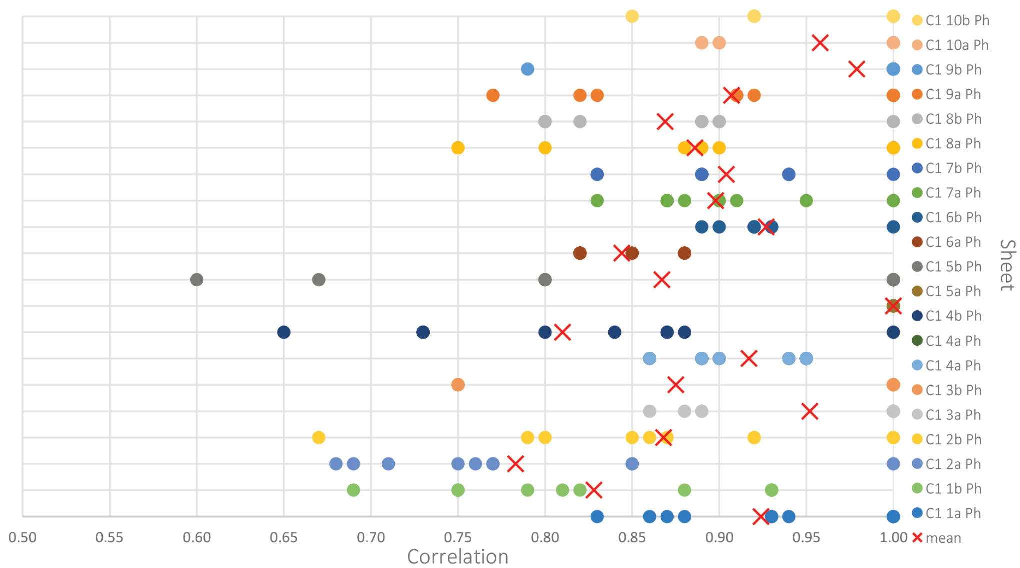

Fig. 11. Correlation ranges for comparisons of intra-source transforms(C1_1-10), using Adobe Photoshop.

Variability analysis between the same types of objects. Comparison of intra-source samples

In the further part of the research, analysis was made of the correlation levels between samples from two reams of the same type of paper, i.e. between different objects from the same source (samples A1_1-25 vs. A2_1-25) (Fig. 12).

A comparison of 410 pairs of characteristic points showed a correlation between samples ranging from 0.53 to 0.95, with mean and median correlation of 0.73 and 0.74, respectively (Fig. 13). This implies that although no pair of samples were found to be completely identical, the minimum number of correlating characteristic points for two samples was higher than 50%.

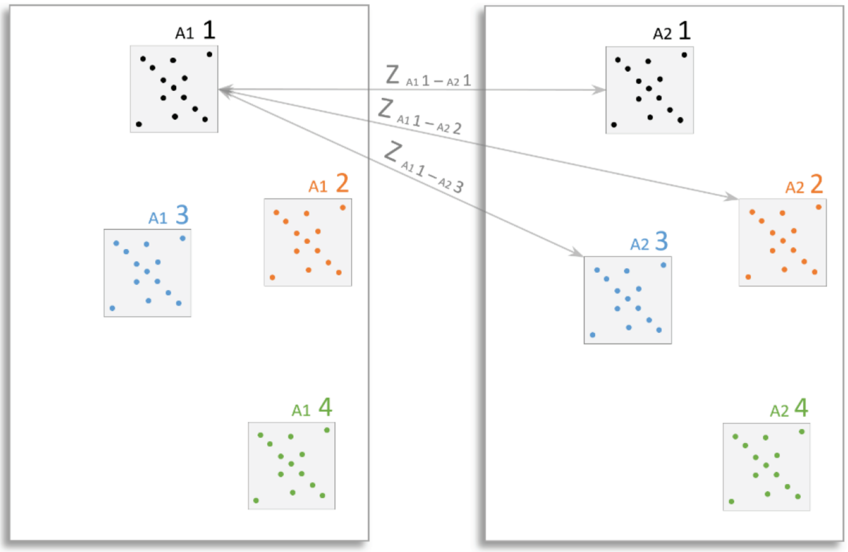

Fig. 12. Comparison of samples from two reams of the same type of paper.

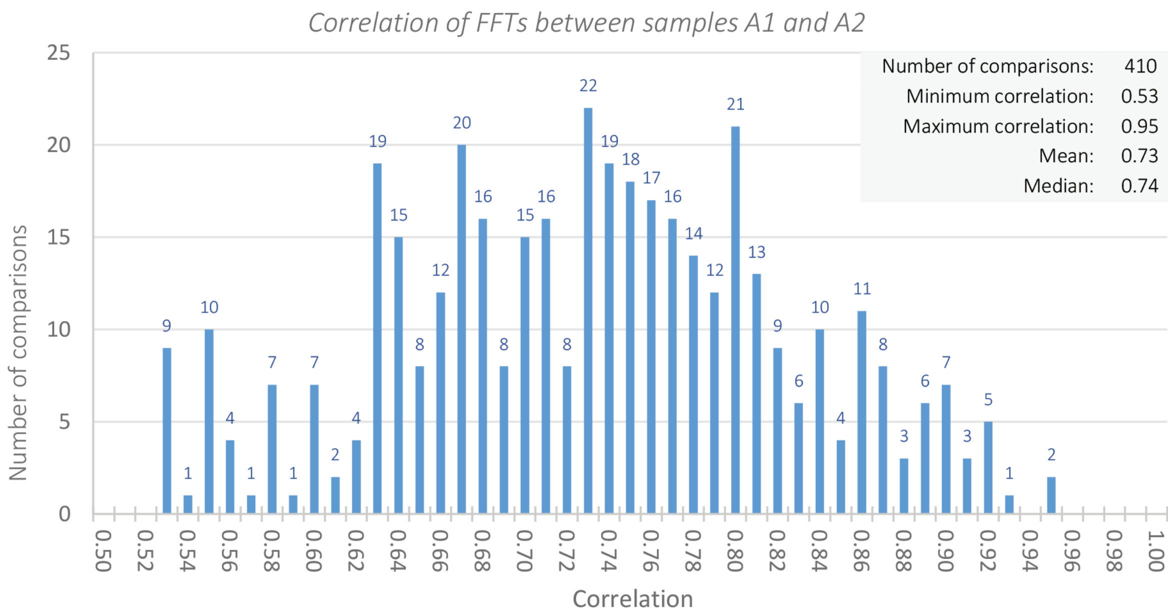

Fig. 13. Correlation of FFTs between samples A1 and A2.

Variability analysis between different types of objects. Comparison of inter-source samples

Next, the correlation between pairs of inter-source samples was examined. For this purpose, the FFTs obtained from samples of paper produced by two different manufacturers were compared. These were marked A2_1-25 and B1_1-25 (348 comparisons were made using the ImageJ-based algorithm). Additionally, the comparisons were made between paper samples of unknown origin—marked group C for this research. Between the samples of unknown origin, both automatic and manual comparison algorithms were used to analyze the same pairs of paper (600 comparisons in total).

Consequently, when comparing samples A2 and B1, the obtained correlation range was within 0.00 to 0.22, with the mean and median of 0.07 and 0.08 (Fig. 14). The most common value was a correlation of 0.00, which means that in 75 comparisons there were no characteristic points in the same position in the two compared FFTs. Furthermore, in the largest number of comparisons no common characteristic points were found between the two transforms in group C, regardless of the algorithm used in the research (Fig. 15–16). The highest correlation level, of 0.46, was obtained in a single comparison, in which 12 correlated scores on 26 characteristic points were obtained. The average correlation between the paper sheets for group C was 0.15 or 0.08, depending on the algorithm used.Correlation

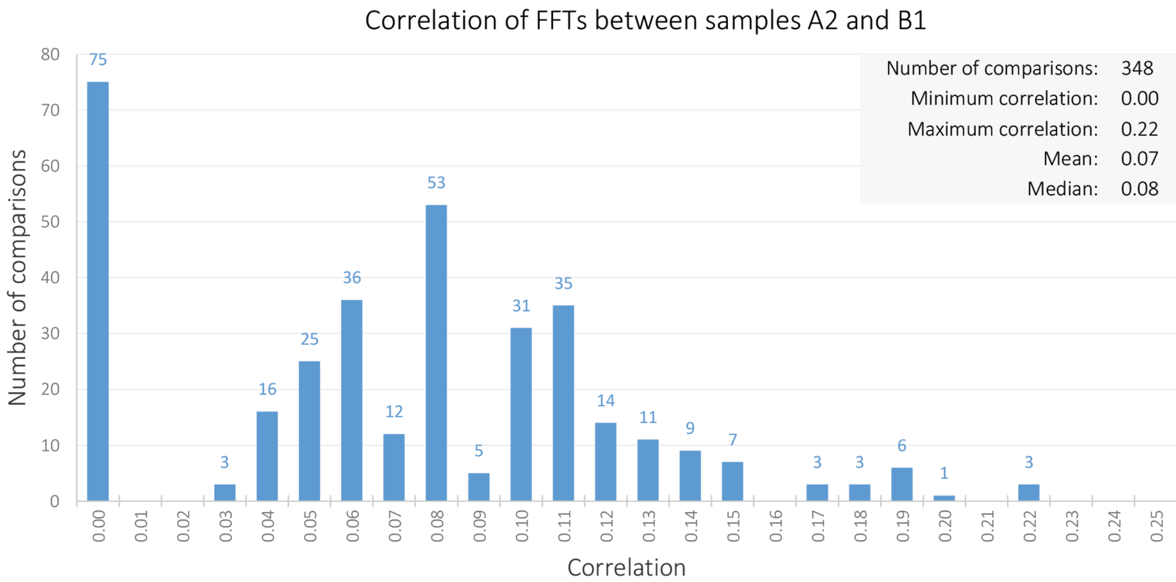

Fig. 14. Correlation of FFTs between samples A2 and B1.

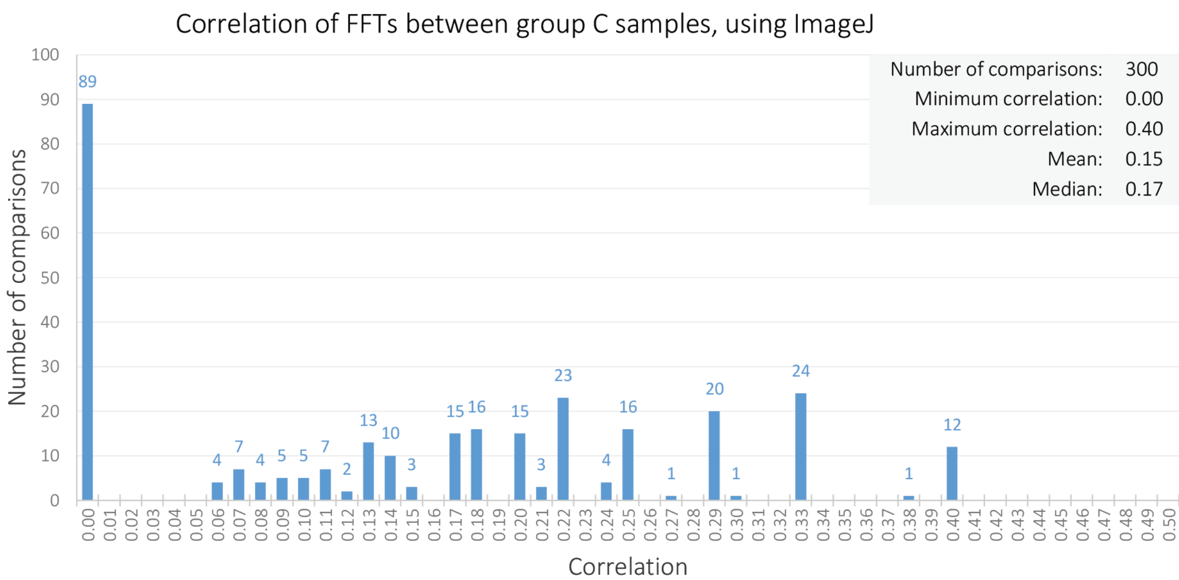

Fig. 15. Correlation of FFTs between group C samples, using ImageJ.

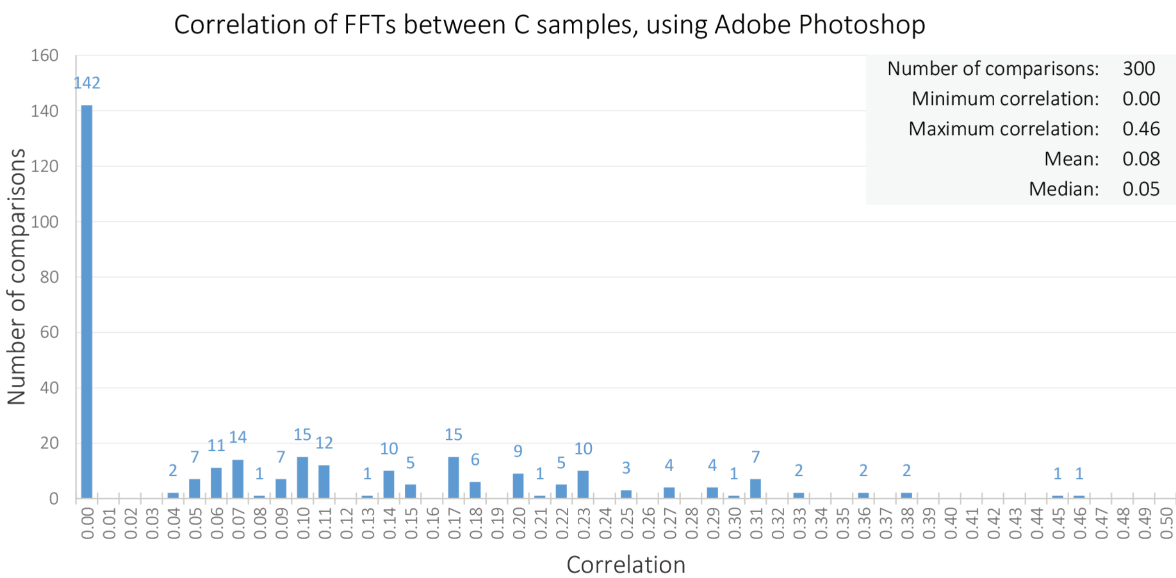

Fig. 16. Correlation of FFTs between group C samples, using Adobe Photoshop.

Results summary

In summary, 2,522 pairs of FFT paper samples were analyzed with the use of two algorithms. This included 1,574 comparisons between intra-source samples and 948 comparisons of inter-source samples. For this last comparison, 50 samples were sourced from two different known manufacturers, as well as 10 samples of unknown origin. For the intra- source samples, the transformer correlation ranged from 0.50 to 1.00 (with the median equal to 0.88), while for the inter-source samples the correlation was in the range of 0.00 to 0.46 (with a correlation median of 0.08) (Fig. 17).

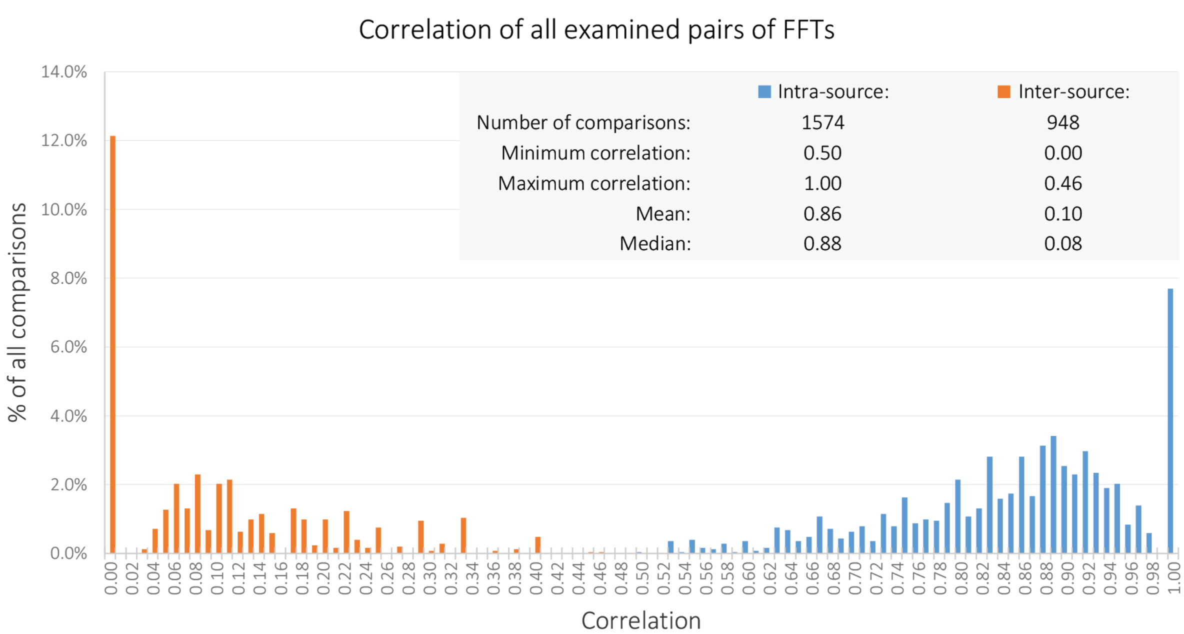

Fig. 17. Correlation of all examined pairs of FFTs.

Conclusions

The results that we obtained prove that the FFT transformation analysis method is a very effective tool in comparing paper samples and determining whether they originated from the same source or from different sources, for example, from different batches of the same product or from different manufacturers.

The results of the paper sample comparisons, from both the same manufacturer and from different sources, showed that the manual and automatic algorithms used in the research can achieve comparable results, which indicates that none of the applied study approaches had a significant advantage over the other.

In addition, none of the methods gave a false positive or false negative result, which was inconsistent with the expected results over 2,522 transform comparisons of two paper samples (correlated or uncorrelated). Moreover, the comparisons made it possible to determine the correlation ranges for samples of paper of both the same and different origin, and what is very important here is that they are separate from each other (from 0 to 0.46 for pairs of samples from different sources, and from 0.50 to 1.00 for pairs of samples from the same source).

It should also be noted that sheets of paper are heterogeneous, which is reflected in the FFTs changing slightly, depending on the location from which the test sample was obtained and then scanned. It is also not without significance that the transformations of the front and reverse of a sheet of paper can differ significantly from one another. For this reason, conclusions about the common or different origins of sheets of paper should be made not on the basis of a comparison of one pair of FFTs, but by comparison of the entire set of paper, considering both the front and reverse sides. For example, for two samples, the correlation of the reverse sides was a relatively high 0.46, and it is worth noting here that the comparison of their reverse sides resulted in a correlation of 0.00. Similarly, for the correlated samples with the lowest correlation of 0.50, the correlation for their reverse sides was 0.83. Thus, it is reasonable to state that comparing two sheets of paper, both their front and reverse sides, can facilitate the interpretation of the obtained results and the formulation of conclusions as to the origin of the compared sheets of paper.

Further validation of the FFT transformation analysis method should be pursued, for example, by extension with examination of the potential influence of intensive use of paper, or of the wetting process of paper, on the correlation parameter of the two FFT samples.

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