Research of Elastic Parameters of Paper and Prints

S Grigaliūnienė[1], V Turla[2], J Sidaravičius[3], P Ragauskas[4] and A Kilikevičius[5]
[1, 2, 3, 5] Vilnius Gediminas Technical University, 28 Basanavičiaus str., LT-10225 Vilnius
[4] Vilnius Gediminas Technical University, 11 Sauletekio al., LT-10105 Vilnius

E-mail: simona.grigaliuniene@vgtu.lt

Abstract. Knowledge of the elastic properties of prints during printing processes is essential in printing presses. A computational inverse technique is presented to determine the elastic properties of materials. An effective technique for identification of elastic properties of prints consisting of the paper and several layers of ink and varnish is based on experimental data of modal vibration testing and finite element modelling. The aim of finite element modelling and optimization is to guess the material properties obtaining the same vibration frequencies and modes while test specimen is loaded in the same way as on printing press. Proposed technique can be used for the printing process modelling as non-destructive method during the initial design stage.

1. Introduction

Today printing industry continues to grow, and a lot of effort is put into the development of new and improved technologies and products. With this increased growth the need for quality assessment also increases, for example to evaluate if new technologies outperform existing technologies, or to compare different products in order to find the best one [1].

Composite material concept can be applied both for paper and printouts. Compared to homogeneous material, properties of composite materials are not only different, but have advantage in most cases [3-5].

Elasticity parameters are important not during the printing process. The main characteristics outlining elasticity parameters of the product are Poisson's ratio and modulus of elasticity. Important is that values of these parameters are different for paper casting directions – longitudinal and transverse [6], therefore, the paper is considered as orthotropic material.

Paper elasticity parameters described and studied in a number of publications [6-9]. Most of them describes comparison of theoretical and experimentally measured or calculated values of elasticity parameters. Theoretical and experimental results reviewed in [2] showed that in terms of the transverse direction of the paper casting, elasticity parameter values becomes greater compared with a printed paper than just plain paper.

In this paper properties identification technology of the printouts is described, which is based on vibration tests and numerical material model [10-11]. In abovementioned works elastic properties of composite materials are identified. Paper is considered as single-layered, covered with paint and/or lacquered – multi-layered composite material.

2. Problem formulation

Proposed elastic material parameters identification technology involves vibration testing carried out on an experimental research equipment [12] and mathematical material model. Sample eigen-frequencies and the corresponding mode shapes are obtained from vibration test. In the mathematical model elastic properties are alternated until the mathematical model eigen-frequencies correspond with vibration testing frequencies. Then it is assumed that chosen in such a way elastic parameters correspond to the real values. Obtained elastic properties are for the whole specimen but not of the particular layer of the specimen.

Frequencies of paper specimen were obtained from natural experiment. During numerical analysis of

[1] Corresponding author

the paper dynamics the known in advance properties of paper were taken: length of the paper, width, thickness, Poisson's ratio, modulus of elasticity and density.

The elastic properties identification is formulated as an optimization problem, where the discrepancies between mathematical model of specimen and the experimental vibration data are minimized. The problem could be stated as follows:

$$\text{Minimize } F(X)=\sum_{i=1}^{n}\left(\frac{f_i^{FEM}-f_i^{NE}}{f_i^{NE}}\right)^2, \text{ subject to } \underline{x_i} \le x_i \le \overline{x_i},\ i=1,2,3,...,m,$$

where F is the objective function of the design variables $X=[x_1,x_2,x_3,...,x_m]$. Variable m is the number of design variables x_i. The eigenfrequency from vibration test denoted as f_i^{NE} (NE – natural experiment); from finite mathematical model is represented as f_i^{FEM} (FEM – finite element method). The number of natural frequencies in objective function is n. The second power makes the objective function always positive. Line under and over in design variable represent lower and upper bounds.

The paper is modeled as an orthotropic material; therefore it can be described by six independent elastic parameters:

$$\begin{aligned}&E_1,\ E_2=E_3,\ \nu_{12}=\nu_{13},\ \nu_{23},\\ &G_{12}=G_{13},\ G_{23}=E_2/2(1+\nu_{23})\end{aligned} \tag{1}$$

However, in order to simplify the three-dimensional identification problem to the two dimensional one, the following assumptions are introduced:

$$E_1,\ E_2=E_3,\ \nu_{12}=\nu_{13}=\nu_{23},\ G_{12}=G_{13}=G_{23} \tag{2}$$

3. Experiment

Sample POP1 is plain paper without any coating. Selecting such material helps verify reliability of results of more complex specimens. Only several natural frequencies were introduced into identification since determination of all sequence is complicated. The natural and numerical experiment eigen-frequencies has significant mismatch, caused by poor identification of natural frequencies of specimen. Nevertheless comparison of eigenfrequencies of identified and calculated eigenfrequencies suggests that the mathematical model of material is developed properly, i.e. mathematical model meets real specimen and one can be used in further experiments with more complex specimens. In the Table 1 are presented identified and known elastic parameters of paper and the percentage difference between them.

Table 1. Identified elastic parameters.

Elastic parameters	POP1		
	Reference	Identified	Δ, %
E_1, GPa	1.1E+09	1.22E+09	21.54
E_2, GPa	0.34E+9	3.34E+08	14.3
ν_{12}	0.40	0.39076	2.31
ν_{23}	0.14	-	-
Objective function	-	0.0354506	-

Identification and analysis of elastic parameters of sample POP1 shows, that material properties of paper were identified with poor accuracy, since high order eigenfrequencies has less sensitivity to change of elastic properties in mathematical model that first ones. This and comparison of results of previous work [12] suggests, that only first several modes of spectrum must be introduced into identification.

Sample POP2 is fully covered with the ink and varnish paper. Only several natural frequencies were introduced into identification since determination of some is complicated.

In the Table 2 are presented identified and known elastic parameters of sample and the percentage difference between them. It must be noted that in column "Reference" are presented elastic properties of plain paper, since ones of printout are not known.

Table 2. Identified elastic parameters.

Elastic parameters	POP2 (100% covered)		
	Reference	Identified	Δ, %
E_1, GPa	1.0E+09	1.43E+09	43.3
E_2, GPa	0.39E+9	1.48E+09	280
ν_{12}	0.40	0.0659	83.525
ν_{23}	0.14	-	-
Objective function	-	0.001254469	-

Observed discrepancies in Table 2 should be not considered as really existing. It is seen that applying a uniform coating on paper turns it from orthotropic to isotropic material, i.e. in plane properties of the material in perpendicular and transverse directions become similar. This was also proved in previous paper [12]. It can be assumed, that identification of elastic characteristics of such sample could be sufficiently accurate since elastic parameters of isotropic material are identified with sufficient accuracy, as it has been shown with sample POP1.

In this case, it can be assumed that it is necessary to take into account possible changes in orthotropy direction. This was theoretically proved in previous paper [12]. Elastic parameters of such sample can be determined as accurately as any orthotropic material. It was already proven during the test of sample POP1.

Sample POP3 not completely covered with ink and completely covered with varnish paper. In the Table 3 are presented identified and known elastic parameters of paper and the percentage difference between them. In column "Reference" elastic properties of plain paper are presented.

Discrepancies in Table 3 should be not considered as really existing since properties of such print is not known. It is seen that applying a uniform coating on paper turns it from orthotropic to isotropic material, i.e. value of Young's modulus E_1 becomes smaller than E_2.

Table 3. Identified elastic parameters.

Elastic parameters	POP3 (14% covered)		
	Reference	Identified	Δ, %
E_1, GPa	1.0E+09	5.87e+009	487
E_2, GPa	0.39E+09	4.87e+010	12387
ν_{12}	0.40	0.0632	84.2
ν_{23}	0.14	-	-
Objective function	-	0.0264487	-

4. Conclusions

The possibility to determine the elastic constants of printouts using the combination of finite element modeling and genetic algorithm was shown on previous paper [12]. The repeatability and accuracy of the proposed inverse determination method is verified. The investigation of the two samples of printouts also proves that the elastic properties identification technique is appropriate.

Theoretical and practical experiments reviewed in [1] claims that the elastic properties of printout changes in the way that from orthotropic material prints turn to isotropic because ink effects paper structure. This was once more confirmed by the present and previous [12] works and proves reliability of the proposed technology for the identification of elastic properties of printouts.

It was stated that amount and sequence of eigenfrequencies used in identification process must be composed according identification results. This will be analysed in future investigations.

References

[1] M Pedersen, N Bonnier, J Y Hardeberg and F Albregtsen 2011 Image quality metrics for evaluation of print quality *Proc. of SPIE-IS&T Electronic Imaging SPIE* **7867(786702)**

[2] A Kabelkaitė 2009 Investigation of influence of the running direction of paper and cardboard and defects of material to the eigenmodes of vibrations *Doctoral dissertation* (Kaunas)

[3] S Markulytė, J Sidaravičius and V Turla 2012 Paper and prints as composite materials *Science – Future of Lithuania* **4(6)** 528–532

[4] T A Schaedler, A J Jacobsen, A Torrents, A E Sorensen, J Lian, J R Greer, L Valdevit and W B Carter 2011 Ultralight Metallic Microlattices *Science* **334(6058)** 962–965

[5] A R Ranjbartoreh, B Wang, X Shen and G Wang 2011 Advanced mechanical properties of graphene paper *Journal of applied physics* **109(014306)**

[6] K Niskannen 2008 Paper physics. *Second ed., Finnish Paper Engineers*

[7] J. van Beeck 2008 Paper: a closer study. *Bachelor final project* (Eindhoven)

[8] T Yokoyama and K Nakai 2007 Evaluation of in-plane orthotropic elastic constants of paper and paperboard *In proceeding of: 2007 SEM Annual Conference & Exposition on Experimental and Applied Mechanics*

[9] P L Ridgway, R E Russo, E Lafond, T Jackson and C Habeger 2003 Laser Ultrasonic System for On-Line Measurement of Elastic Properties of Paper *Journal of Pulp and Paper Science* **29(9)** 289–293

[10] P Ragauskas and E Skukis 2007 Material properties identification. Comparison of two techniques *Mechanika* **6(68)** 39–44

[11] P Ragauskas and R Belevičius 2009 Identification of material properties of composite materials *Aviation* (Vilnius, Lithuania) **13(4)** 109

[12] P Ragauskas, S Grigaliūnienė, J Sidaravičius and V Turla 2013 Identification of the Prints Elastic Parameters using Vibrational Methods *Mechatronical Systems and Materials*