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Identification of prints elastic parameters

S. Grigaliūnienė*, V. Turla, P. Ragauskas***, A. Kilikevičius****, J. Sidaravičius*****, E. Jurkonis******

Vilnius Gediminas Technical University, Basanaviciaus 28, 03224 Vilnius, Lithuania, E-mail: simona.grigaliuniene@vgtu.lt

***Vilnius Gediminas Technical University, Basanaviciaus 28, 03224 Vilnius, Lithuania, E-mail: vytautas.turla@vgtu.lt*

****Vilnius Gediminas Technical University, 11 Sauletekio al., 10225 Vilnius, Lithuania, E-mail: paulius.ragauskas@vgtu.lt*

*****Vilnius Gediminas Technical University, Basanaviciaus 28, 03224 Vilnius, Lithuania, E-mail: arturas.kilikevicius@vgtu.lt*

******Vilnius Gediminas Technical University, Basanaviciaus 28, 03224 Vilnius, Lithuania, E-mail: jonas.sidaravicius@vgtu.lt*

*******Vilnius Gediminas Technical University, Basanaviciaus 28, 03224 Vilnius, Lithuania, E-mail: eugenijus.jurkonis@vgtu.lt*

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1. Introduction

Elasticity characteristics of prints (as composite material) are important for both printing and designing products especially package. During printing paper band should be stretched certain force between machine printing sections. Ink layer on the paper changes its elasticity parameters, as well as the dynamic behaviour of the print moving in the press because paper web dynamic properties depend first of all on its elastic properties. As a result, the paper web after coating in each section can behave differently depending on the ink layer thickness, coated area and stretching force. The difference between sections of print dynamic behaviour can affect printing quality as the web may begin to oscillate and will occur register problems.

The main characteristics outlining elasticity parameters of the product are modulus of elasticity (i.e. Young's modulus) and Poisson's ratio. As for the paper, it is important that these parameters essentially depend on the orientation of cellulose fibers and are different in grain direction (machine direction), cross grain direction and z-direction (direction perpendicular to the paper surface), therefore, the paper might be considered as orthotropic material. Paper elastic properties are widely investigated experimentally [1], [2] as well as theoretically [3–6]. Print elastic properties are almost not investigated except several recent attempts [7], [8]. The aim of this work is to investigate the elastic properties of the prints using computational methods.

Natural frequencies of prints are used for identification of mechanical properties (i.e. elasticity properties) by solving problem of reverse engineering. In this paper identification of mechanical properties of prints in context of mode extraction problems are discussed. These problems are caused by fastening and excitation conditions of prints since they are relatively slender. This affects reliability of identification results. Pretension of sample has also considerable impact to spectra of natural frequencies. Performing experiments pretension conditions are attempted to be as close as possible to real ones in printing press. Nevertheless practice shows that aforementioned pretension is not sufficient in all cases attempting to identify enough natural frequencies for identification of elasticity properties [7].

Sample fastening (i.e. constraints) appears challenging when performing vibration analysis of paper prints. One of the main fastening problems is the tension of sample [9-11]. It is well known, that natural frequencies of the body under tension shifts upward. In this case, the prints showed that the more pretension applied on the sample the easier it is to determine natural frequencies due to stiffening of the material. However, there is a tension threshold beyond at which the sample reaches the plastic deformation limit and begins to disintegrate [1]. In order to determine with sufficient accuracy natural frequencies of the print an experiment was performed in which prints on six different papers were stretched by the steadily increasing load and measuring the response of the vibration excitation.

Tests were carried out fastening the two opposite edges of sample (Fig. 1). Sample dimensions – 0.20× ×0.20 m (to clamping guides), thickness varies from 150 to 300 μm. Prints are 100% covered fused toner laser prints. Test conditions are close to the pressrooms conditions: temperature 24°C, relative humidity of 38%. The sample is excited with the piezoelectric transducer contacted with the surface of sample, providing a range of frequencies from 10 Hz to 1000 Hz. Measurement was performed by non-contact method in 15 points, symmetrically arranged on the surface of the sample. Natural frequencies and mode shapes were obtained by modal analysis software. During tests load was increased from 40 N to 480 N every 40 N.

The measurements of each print shows that at a certain tension spectrum of the first eight modes get stabilized. Number of modes is selected on the basis of current experience that this amount of modes is sufficient for the effective identification of elasticity parameters of orthotropic material.

After determination of pretension threshold for each sample, identification procedure was performed. Technique used for identification of parameters of elasticity parameters of prints is designed to input the vibration data using external files and employing finite element package ANSYS [12] for the numerical simulation.

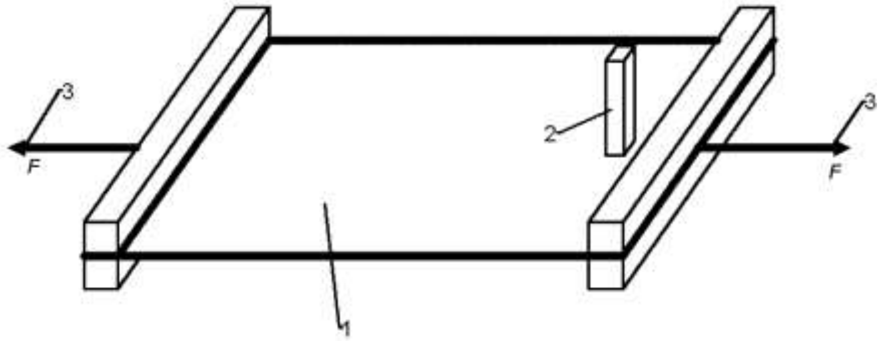

Fig. 1 Scheme of test equipment: *1* – print or paper; *2* – piezoelectric transducer; *3* – tension direction

Different bending plate finite elements can be employed depending on the specimen parameters. Genetic algorithm is used as an optimization tool.

Proposed identification technology of elasticity parameters involves vibration testing carried out on an experimental research equipment and mathematical material model [8]. Natural frequencies of sample and the corresponding mode shapes are obtained from vibration test. In the mathematical model elasticity properties are alternated until the natural frequencies of mathematical model correspond with frequencies of vibration testing. Then it is assumed that chosen in such a way elasticity parameters correspond to the real values. Obtained elasticity properties are for the whole specimen but not of the particular layer of one [2], [13-15].

Identification of the elasticity properties is formulated as an optimization problem, where the discrepancies between mathematical model of specimen and the experimental vibration data are minimized [16]. The problem could be stated as follows:

$$\text{minimize } F(X)=\sum_{i=1}^{n}\frac{(f_i^{FEM}-f_i^{NE})^2}{f_i^{NE}},$$

$$\text{subject to } \underline{x_i}\le x_i\le \overline{x_i} \quad i=1,2,3,\ldots,m, \qquad (1)$$

where F is the objective function of the design variables $X = [x_1, x_2, x_3, \ldots, x_m]$. 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 print is modelled as an orthotropic material and therefore it can be described by six independent elasticity parameters:

$$E_1,\ E_2=E_3,\ \nu_{12}=\nu_{13},\ \nu_{23},$$
$$G_{12}=G_{13},\ G_{23}=E_2/2(1-\nu_{23}). \qquad (2)$$

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

$$E_1,\ E_2=E_3,\ \nu_{12}=\nu_{13}=\nu_{23},$$
$$G_{12}=G_{13}=G_{23}. \qquad (3)$$

The process of identification starts with the generation of a random initial population of sets of material properties values. Each design is randomly formed by choosing the elasticity properties values within particular interval of positive values. Then real eigenvalue analysis is carried out. In the post-processing stage, elastic constants and the desired first fundamental frequencies extracted. The objective function value is calculated every iteration; ANSYS is loaded to obtain natural frequencies of material specimens with certain elasticity properties. The fitness processor begins to operate at the end of the population processing, evaluating the objective function for each design. Goal of the optimization is to find a set of elastic constants in order that the outputs from the numerical code fit the experimental results [17].

2. Experiments

This work is based on previously performed tests which revealed minimal initial pretension values of the sample in vibration tests [7]. List of samples and identified pretension force range values are presented in the Table 1. Geometrical characteristics and paper elasticity parameters [3] are presented in the Table 2. Tests of six different types of samples (coated with same ink and uniform thickness) revealed that in order to obtain reliable results of modal analysis, i.e. to record stably the first eight modes, sample must be under certain pretension, which differs due to print thickness and the amount of ink. Since in tests was used the same ink coating (0.005 mm), differences are caused only by thickness of paper. All samples are square-shaped and are fully covered with ink.

Differences between the minimum loads at which reliable results of modal analysis obtained are associated with the sample thickness and physical properties of the paper, as the layer of paint of samples is the same. Also paint absorption properties of sample should not be dismissed, which are not analysed in this paper.

During identification procedure eight modes of specimens were calculated (Fig. 2). Due to fact that general properties of elasticity are identified, obtained mode shapes are similar for all samples nevertheless thickness is different; mode shapes for each specimen are not provided.

It should be noted that the value of strain is selected not on the lower limit of identified range trying to avoid the possible inaccuracies during identification of elasticity parameters. It is assumed that the sample vibrations stabilize when first preferred modes of the spectrum can be identified. Since to the stability of identification of modes the load step increasing has a significant influence

Table 1

Sample list, description and pretension range

No	Name	Paper type	Grammage, g/m^2	Tension range, N/mm^2
0	Sample 0	Cardboard “Arktika”	280	4.1–4.5
1	Sample 1	Coated paper “Galerie art silk”	150	3.3–6.6
2	Sample 2	Non-coated paper “4cc”	200	6.4–10.9
3	Sample 3	Cardboard “Arktika”	230	5.3–7.1
4	Sample 4	Non-coated paper “4cc”	280	6.7–8.0
5	Sample 5	Coated paper “Galerie art silk”	300	3.3–6.6

Table 2

Geometrical and elasticity parameters of papers

Parameter	Value
Length (a), mm	200
Width (b), mm	200
Thickness, μm	120–440
E_1, GPa	~1.0
E_2, GPa	~0.39
ν_{12}	~0.40
ν_{23}	~0.14
Density, kg/m^3	800

(described in the previous work [7]), for the identification of the elasticity parameters higher values of stretching are chosen. Although the values of stretching at the process of identification does not reaches those in printing press, the investigation goals are achieved, i.e. the main elasticity parameters of the prints are identified well. Identified elasticity parameters are presented in Table 3.

Identification of the print’s elasticity parameters shows that stretching increases value of longitudinal Young's modulus (about 10 times), but the value of transversal Young modulus remains of the same order. This shows that stretched specimen increases its stiffness in the longitudinal direction.

Poisson's ratio in these experiments is identified with poor precision (Table 3, ν_{12} unacceptable values scatter) because of insufficient thickness of the sample. On the other hand its influence to the eigenfrequencies of the sample in our case low. From other works [18] it is known, that influence of the Poisson's ratio to the samples eigenfrequencies can be increased by proper adjusting sample width length ratio of a flat specimen. This work will be carried out in the future.

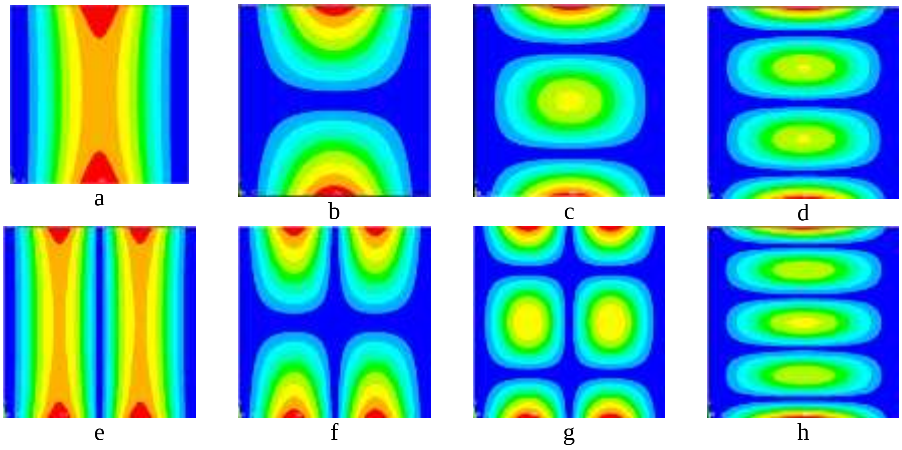

Fig. 2 Calculated mode shapes: (a–h) – 1 to 8 modes respectively

Table 3

Identified elasticity parameters of prints

Elasticity parameters	Plain paper	Sample 0	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
E_1, GPa	1.1	1.94	1.36	2.35	2.28	2.08	8.15
E_2, GPa	0.39	0.870	0.570	0.360	0.275	0.687	0.320
ν_{12}	0.40	0.062188	0.16775	0.036698	0.385496	0.0072405	0.237385
ν_{23}	0.14	–	–	–	–	–	–
Objective function	-	0.0587161	0.0357455	0.111038	0.040874	0.140869	0.0971981
Tension, N/mm^2	-	4.5	5.0	8.2	5.9	7.3	4.0

3. **Conclusions**

Six prints samples of different thickness were involved in this work and elasticity parameters were identified. Samples were fully covered with ink of uniform thickness. Tests revealed that prints change their elasticity properties compared to plain paper. Main difference is observed in longitudinal Young’s modulus change, i.e.

after paper was covered with ink it stiffens and its longitudinal Young's modulus increases up to 10 times. This effect is caused not only by ink layer but by sample pretention also, since stiffness of material depends on tensile force.

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SPAUDINIŲ TAMPRUMO RODIKLIŲ NUSTATYMAS

R e z i u m ė

Spaudinių tamprumo rodikliai skiriasi nuo gryno popieriaus tamprumo rodiklių dėl padengto dažų sluoksnio. Šių rodiklių nustatymui panaudota metodika, paremta eksperimentiniais vibraciniais bandymais ir skaičiavimais, naudojant BEM matematinį modelį. Eksperimentiniu būdu, naudojant specialią įrangą, buvo nustatyta, kokie dažniai atitinka bandinių pirmąsias aštuonias savųjų virpesių modas bei dažnius. Naudojant BEM matematinį modelį ir genetinius algoritmus teoriškai paskaičiuota, prie kokių tamprumo rodiklių gaunami tie patys dažniai ir tos pačios virpesių modos. Tuo būdu identifikuoti spaudinių tamprumo rodikliai šešioms skirtingoms spaudinių rūšims. Įrodyta tokio metodo taikymo galimybė ir nustatyta, kad pagrindinai spaudinių tamprumo rodikliai skiriasi išilgine popieriaus liejimo kryptimi.

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IDENTIFICATION OF PRINTS ELASTIC PARAMETERS

S u m m a r y

Elastic characteristics of plain paper differ from prints elastic characteristics due to coating. For the identification of the elastic characteristics of prints a methodology based on experimental vibration tests and calculations using FEM mathematical model is involved. Using special equipment it was found which frequencies of samples corresponds to first eight natural modes and frequencies. Using FEM and genetic algorithm it was theoretically calculated at which elastic parameters same natural frequencies and modes are obtained. This methodology was used to identify the elastic characteristics of six different prints. It has been shown the possibility of practical application of such methodology and it was found that elastic characteristics of different prints differ in the longitudinal (machine) direction of the paper.

Keywords: prints, vibration testing, elasticity parameters.

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