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Application of Fibre Composite Materials for Increasing the Productivity of Production Machines

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

The paper presents a case study involved in research project. A case study was based on vibrodiagnostics analyses of unwanted vibrations, machine arrangement and usage of composite materials for increasing the productivity. The main requirement was the increase of productivity of flexographic machine keeping the quality of printing. The paper describes the monitoring, evaluating, comparing machine dynamic response, improving the accuracy of mounting, accuracy of individual machine parts in component joints and modal properties of components made from non-conventional materials to achieve the decrease of vibrations and the increase the damping of flexographic printing machine.

Keywords: Vibrodiagnostics control; composite cylinder; printing speed; damping.

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1. INTRODUCTION

The producers invest a lot in upgrading and acquiring new machines and technologies, which allows to be flexible and to produce top-quality competitive products in short time.

The main requirement of printed flexible films producer was the increase of productivity of flexographic machine keeping the quality of printing. The problem was based on solving the source of unwanted limits of vibrations in high speeds that caused the lower printing quality. The paper describes the solution process - methodology that is appropriate for other production machines problems based on large vibrations.

1.1 Macroscopic Dynamic Response of Production Machines

Invoking of mechanical vibrations is inseparable part of operating production machines that present mechanical systems of mass and elastic bodies. Mostly the mechanical vibrations are unwanted regarding both technological process and working environment (noise) and transfer on base of production area.

Dynamic properties of each production machine as complex dynamic system are depending on:

- design (shape and dimensions), material properties of individual parts of machine, e.g. power drive, movement mechanisms etc. and their mutual joint,
- operating conditions, e.g. revolutions, speed, transmitted moment, parameters of technological process.
- physical parameters as machine stiffness, damping and weight.

Mechanical system of flexographic printing machine consists of frame of machine, power drive, central impression cylinder, raster and plate cylinders and their joints (Fig. 1). The basic structure of dynamic system of machine is completed by technological process (printing) itself, friction process (friction in surface contacts, material damping) and power drive process. The linear and angular displacements and their derivations are the outputs that resulting in final quality of product (printing).

General mathematical model of dynamic system (of *n* degrees of freedom) is expressed by *n* differential equation system in form:

$$\mathbf{M}\ddot{\mathbf{q}}(t)+\mathbf{C}\dot{\mathbf{q}}(t)+\mathbf{K}\mathbf{q}(t)=\mathbf{F}(t) \qquad (1)$$

Where **M**, **C**, **K** is matrix of weight, damping and stiffness of mechanical system of *n*x*n* dimension, **F** is vector of load (excitation forces), $\mathbf{q}$, $\dot{\mathbf{q}}$, $\ddot{\mathbf{q}}$ is vector of displacements (linear and angular), velocities and accelerations.

1.2 Microscopic Material Structure Response

The macroscopic dynamic response of structures is important in engineering applications depending on microscopic material structure. [1], [2] The vibrations and shock waves propagate through individual machine tool components assembled in the component joints and functional modules. In ordinary, it is supposed the individual components are made from homogenous and isotropic materials with some material damping. However, the material structure in microscopic level involves some in homogenities (pores, impurities, etc.) that are source of material damping. The different materials forming the composite materials considerably change the wave propagation and material damping. The typology of dis-continuous fibers in composite material is not neglectable. It influences transfer of load and mechanical waves. The oscillation of one particle (atom) is transferred through the binding forces to another one and effects the wave propagation. Naturally, the machine tool damping is caused by forces resisting the relative motion of solid surfaces sliding against each other in mechanical system. [3,4].

Firstly, the waves propagate through the components of machine tool and consequently the waves proceed to environment (air). The sound appears. The noise level is one of quality atributes of operational environment for operational staff. The wave propagation in heterogeneous materials (e.g. fiber composite material) is very complex effect that is object of present research regarding damping and wave dispersion.

The types of waves in solids (3-dimentional elastic medium) are following [5]:

Longitudinal waves occur when the oscillations of particles (e.g. composite material) are parallel to the direction of propagation. The phase velocity c_1 of faster longitudinal wave is given:

$$c_1 = \sqrt{\frac{\lambda + 2G}{\rho}} \quad (2)$$

where λ is Lamé constant, G is shear modulus and ρ is density of material.

Transverse waves occur when a disturbance creates oscillations perpendicular (at right angles) to the propagation (the direction of energy transfer). The phase velocity c_2 is given:

$$c_2 = \sqrt{\frac{G}{\rho}} \quad (3)$$

Rayleigh waves are a type of surface waves that travel near of solids surface (elastic half-space). Their amplitude decrease exponentially as distance from the surface increases. The Rayleigh waves velocity c_R depends on Poisson ratio. The composite particles have the elliptic moving and are damped in direction perpendicular to surface.

Bending waves are waves in structures with finite bending stiffness.

The equations (2) and (3) show that the material constants and material density mainly influenced velocity of waves in material.

2. VIBRODIAGNOSTICS ANALYSIS OF FLEXOPRINTING PROCESS

The printing machines operate the latest flexoprinting and rotogravure technologies that meet demands of customers and also stringent legislative requirements. Flexography is a form of printing process using a flexible image plates on which the printing areas are above the non-printing areas. Flexographic printing is a modern printing technology and dynamic developing printing branch. The different printing plates are for different colours. The rotary principle of printing enables the simple control of printing speed. The printed flexible films (bags, cartons, labels etc.) are intended for packaging in food and chemical industry.

Fig. 1 shows the schema of printing section of flexographic printing machine. The flexible thin plastic (film) passes the individual printing positions and it enters the drying section. The each printing position involves plate and raster (anilox) cylinders with inking unit of individual colour. The raster cylinder has small holes (cells) or grooves which are filed by colour ink while it rotates. The ink is applied on relief of plate. The profile of plate is imprinted on flexible film that is passing to another printing position with another plate and colour. There are the 4-, 6- 8-, 10-coloured printing machines with different printing width (800 - 1 870 mm) and different speeds of printing (100 - 1 000 m/min).

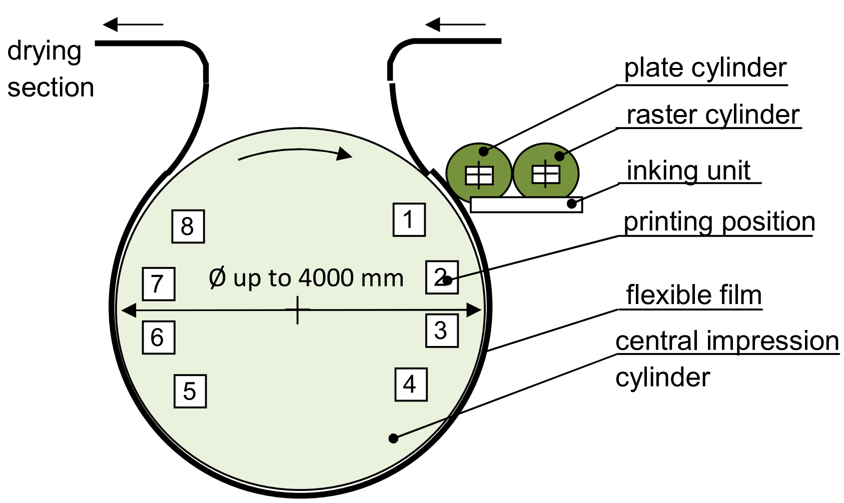

Fig. 1. Schema of printing section

Dynamic impact is caused by impact between plate cylinder and external cylindrical surface of central impression cylinder. The high vibration of plate cylinder causes low quality of printing, gaps or overlapping colours. If the pattern (image) consists of several colours, the individual colours are not allowed to be overlapped. The gaps between colours are unwanted.

The measurements were made in cooperation with Technical Diagnostics, ltd. to determine the forces or localities that causing repeated impact, the envelope method was used. Acceleration Enveloping (Fig. 2) detects repeating vibration signals in high frequencies range. The same method is used for analyse of roller bearings and teeth frequencies where the source of repeating signal is crossing the damaged place by rotational motion. [6,7].

Acceleration Enveloping confirms that repeating impact is caused by straight edge of pattern at plate cylinder into central cylinder. At same time the mentioned method allows to identify the time of damping (Fig. 2). While vibration is being damped, the area of flexible film is without colour. This low class quality part of printing can be visible only by use of microscope. But if the higher printing speed is used, the impact force is higher, the time of damping is longer and quality of printing is worse. Such printing conditions bring film with uncoloured areas that are visible by eyes and/or individual colours are overlapped. There are more or less suitable reliefs of printing plates in term of vibrations formation. The most difficult printing design involves straight rising edges causing the creation of higher impacts (Fig. 3). The straight rising edge is the edge that is perpendicularly to film winding direction and it is at least appropriate. The more appropriate are sloping edges. The printing speed is influenced by unwanted straight rising edges.

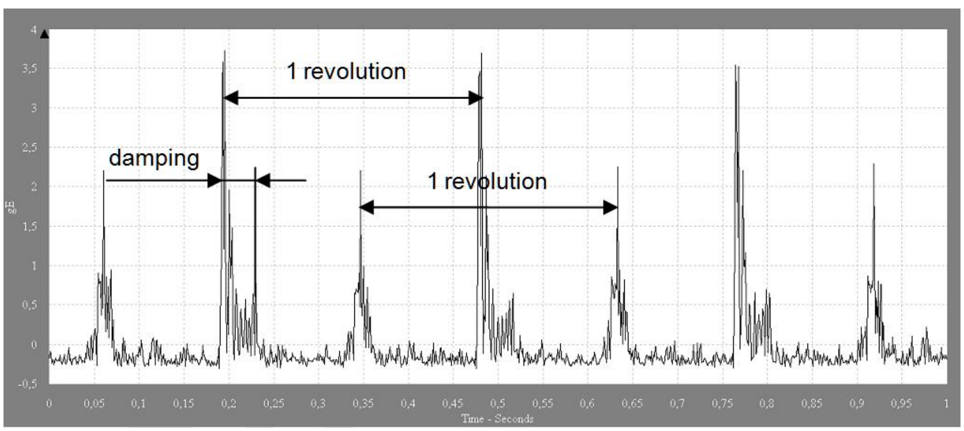

Fig. 2. Time record (1s) of acceleration enveloping

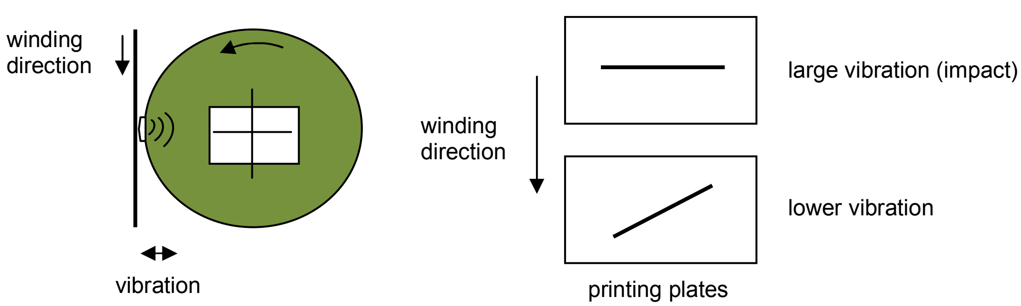

Fig. 3. Vibration source and location of edges at printing plates

The magnitude of vibrations is influenced by material of plate situated on plate cylinder. The plates are made of four kinds of rubber differ by elasticity, wearing and stability of printing quality.

The analyses of dynamic processes of production machines show two areas of improving the production keeping the quality. The resources of improving the productivity:

- Vibrodiagnostics control and improving the accuracy
  - of mounting,
  - of individual machine parts in component joints,
- Use of composite materials and structures.

2.1 Vibrations and Component Joints Accuracy

The next section describes the problem solution through vibrodiagnostics control and improving the accuracy of mounting and individual machine parts in component joints.

The measured points for monitoring dynamic signal were following:

- printing position 1-8,
- plate and raster cylinders,
- horizontal and vertical direction of vibrations,
- operator and drive sides.

All together 64 (8x2x2x2) outputs of measured points are for evaluation. To decrease the vibration, the following arrangement work was made on selected flexographic printing machines:

- exchange of bearing mounting at operator and drive side,
- setting of radial clearance of main needle bearings by selection of shaft tolerance,
- control of radial run out of cylinders surface and tolerance of concentricity compared with axes of shaft bearing cylinders.

The correct operation of flexographic printing machines is strongly influenced by radial clearance of needle bearing. [8,9] The magnitude of radial clearance influences the size of loaded area in bearing; it means that the smaller clearance, the more solids of revolution carry the radial load and the load of each solid of revolution are lower. Moreover, the ability of damping of dynamic excitation and vibrations generated by printing process is influenced by radial clearance. Table 1 shows the standard radial clearances of needle bearings. The optimal function of needle bearing is guaranteed by producer if the recommended radial clearance in range 30 – 50 μm is used.

The standard needle bearings are produced with normal radial clearance. The inner races are thin-walled and the required clearances are achieved by shaft tolerance (Table 1). In case of special inner bearing race (for example wider bearing for axial displacement of cylinder) it is needful to choose tolerance of shaft and tolerance of race surface diameter. The final measure of race surface after mounting (fixing the inner race on the shaft) should guarantee working clearance in recommended range of 30 – 50 μm. In such case it is suitable to grind the race surface and set the required measure after mounting on the shaft (cylinder).

The estimation of the state of measured machine elements is according to standard STN ISO 10816-3 (Slovak Technical Standard modified according to the International Organisation for Standardization): Measuring of vibrations of revolving machines. Table 2 introduces the recommended limits of Warning and Danger of summing vibrations according to mentioned standard.

Table 1. Standard radial clearance of needle bearing

Needle bearing	Radial clearance [μm]			Tolerance of shaft for mounting of inner race		
	Lower C2	Normal N	Higher C3	Lower	Normal	Higher
RNA 6913	10–40	40–70	60–90	k5	h5	g6
RNA 6916	10–45	40–75	65–100	k5	h5	f6

Table 2. Alarms limits and measured values before and after arrangement work (assortment X)

			Velocity [mm/s]	Acceleration [g]	Time Acc [g]	
Alarm 1:Warning			2.8	0.15	1.5	
Alarm 2: Danger			4.5	0.25	2.0	
Before	OS	HD	*5.84*	*0.34*	*2.8*	Alarm 2: Danger
Before	position 8	VD	1.78	0.15	*2.0*	Alarm 2: Danger
Before	DS	HD	*6.94*	*0.28*	*2.2*	Alarm 2: Danger
Before	position 8	VD	1.56	0.10	*1.8*	Alarm 2: Danger
After	OS	HD	1.32	0.10	1.4	No alarm
After	position 8	VD	1.00	0.10	1.2	No alarm
After	DS	HD	1.04	0.08	0.8	No alarm
After	position 8	VD	0.59	0.09	1.0	No alarm

Moreover, Table 2 provides the values of measured vibrations on printing position 8 at the operator side (OS) and drive side (DS) before arrangement work and the measured values at the same locations after arrangement work, i.e. after change the bearings and control of rotational accuracy of cylinders. The vibrations in horizontal direction (HD) are 5-times larger than in vertical direction (VD). The italic and bolt numbers are the values over Alarm 2: Danger.

Comparing the measured values introduced in Table 2, it is obvious that after arrangement work strong decreasing of vibrations and dynamic excitation of printing position appeared that results in increasing the quality of printing.

3. USE OF COMPOSITE STRUCTURES FOR FLEXOPRINTING

Another stage of the vibration problem decrease can be solved through the use of material properties of composite materials.

The structure with complex shape involves each mentioned basic waves. The fibres/dis-continuous fibres/particles in composite materials cause very important effect: Interference, absorption, reflection that allow the damping and dispersing of waves by material itself. The wave in homogeneous material is not influenced, it reflexes only on the body border and such wave interacts with other propagating wave. In non-homogeneous material that consists of particles and fibres, the interaction (interference, absorption, reflection) of wave/s is situated on the border of material in homogenities. The waves invoke the move and friction on fiber-matrix interface. The decohesion and the reversing recohesion and fibers rearrangement appear in the fiber ends. The mentioned effects are resource of mechanical energy absorption. The ability of absorption is increased by addition of lubricating material (polyvinyl alcohol PVA, silicon oil) that make worse the bonding on fiber-matrix interface. The composite materials made without interlayer have high shear strength on the fiber-matrix interface, but the low resistance on longitudinal cracks at fiber-matrix interface. The suitable composite material has improved damping properties, good fatigue strength and high static strength.

3.1 Application of Fiber Composite Components

Despite the described arrangement work in chapter 2 and very good results, there was a possibility to improve results, printing quality and speed. The special plate cylinders based on composite materials were applied. The describing step required larger expenses for investment comparing with previous arrangement work.

In ordinary, the plate cylinders consist of core and casing (Fig. 4). The different material combinations can be used:

- steel core – composite casing,
- composite core - composite casing.

The composite casings consists of multilayer sandwich, composite cores are made of fibre composites (Fig. 4).

The various producers of composite printing cylinders differentiate by inner structure and material of cylinder (Fig. 5).

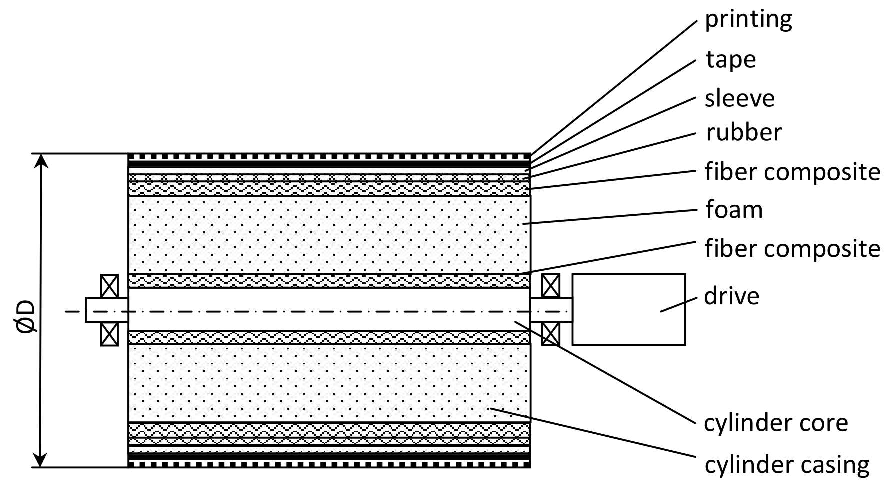

Fig. 4. Multilayered sandwich plate cylinder

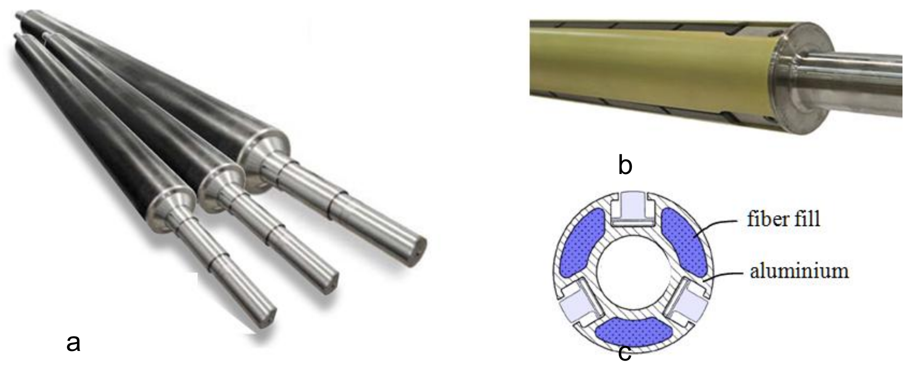

Fig. 5. Composite cores of cylinders

The cylinders in Fig. 5a consist of winded high/super-high module carbon fibres. The cylinder in Figs. 5b, c has aluminium profile with filling of fibers oriented in one direction that increases the stiffening effect. The producer of such cylinders notifies increasing of printing speed up to 200%. The research and development in field of advanced applications of composite materials is in progress. The printing cylinder cores showed in Fig. 5a were used in presented application.

One of many advantages of the composite cylinders is their minimal deflection regarding the high cylinder stiffness. The Young's module of composite cylinders is about 400 GPa. Further, composite cylinders have low weight and need less energy to drive. They are called superlight comparing with steel cylinders. This is important factor in economy of application.

3.2 Numerical Simulation of Wave Propagation

The presented numerical simulation of material damping in microscopic level concerns 2D numerical model (plain strain), Fig. 6, with reinforcing straight fibers/particles that are much stiffer than matrix. It presents partial results of research projects on which we collaborated. (more in [10,11]). The LS DYNA model involves straight fibers/particles of $R1$ radius situated in layers parallel to surface with distance $\Delta_1=\Delta_2=3R$ between each other. The ratio of Young's modules matrix and fiber E_m:E_f is 1:100. The load of shock wave raising in time 0.05μs from 0 up to 31.5 MPa and backward in same time it falls to 0. The following simulation acknowledges and documents significant damping effect in materials reinforced by fibers/particles.

Initially, the shock wave propagates without any defect (Fig. 7a). Passing the first layer of fibers/particles, the reflection and interference appears (Fig. 7b). Passing the all fibers/particles layers, the dispersed shock wave is evident (Fig. 7c).

Table 3 summarizes results of average stress in layers of model defined by individual points showed in Fig. 6. The notable decrease of stress is visible due to interaction of shock waves and fibers/particles. The damping is obtained purely by absorption, reflection and interference of waves with fibers/particles. The decrease of values concerns also displacements.

Table 3. Average stress in layers under surface

Layer through points	Stress [MPa]
1-6-11	42.54
2-7-12	30.31
3-8-13	16.33
4-9-14	11.73
5-10-15	9.04

3.3 Experimental Testing of Dynamic Properties

In cooperation with company Technical Diagnostics, ltd., the bump test was realized to analyze the structural modal response of material. The object is impacted with a massive object such as a hammer. The object responds to the impact by a vibration. The resulting spectrum contains peaks that correspond to the natural frequencies or "resonances" of object. The measuring was made in radial direction (bending), twice per each sample (two perpendicular directions).

The tested samples were pipes with dimensions: outer diameter *D*=12 mm, inner diameter *d*=8mm, length *L*=110 mm. The samples were made of glass (SiO_2), oxide ceramics (corundum Al_2O_3) and composite of ceramics matrix with short fibers of carbon (C/SiC). The measured values are in Table 4 and Fig. 8. The samples are different for their material and microstructure. Material properties of sample 4 are directional.

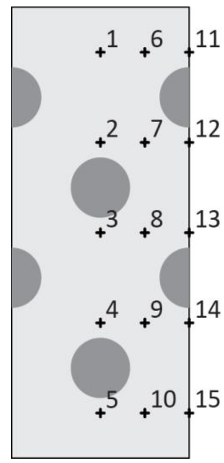

Fig. 6. 2D model of fibers/particles reinforced composite

Sample 1: Glass SiO_2 is homogenous, amorphous, isotropic, solid and brittle material in metastabile state. It involves mostly siliceous sand, soda, oxides of alkali metals, calcite. Some material properties: Tensile strength 33 MPa, density 2.53 g/cm^3.

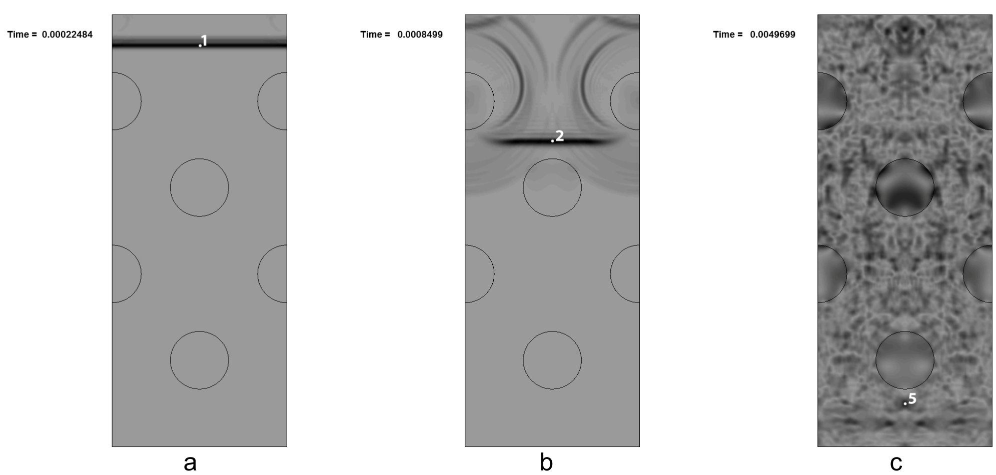

Fig. 7. Effective stress distribution passing the points (1, 2, 5)

Table 4. Measured values

Number of sample	Material	Natural frequency [Hz]		Damping time [10^{-3}s]		Note
		direction 1	direction 2	direction 1	direction 2	
1	SiO_2	4378	4380	11.0	11.6	narrow freq. zone
2	Al_2O_3	5806	5808	145.4	151.1	narrow freq. zone
3	C/SiC	6816	6803	6.7	6.9	large freq. zone
4	C/SiC⊥	6690	6693	5.4	7.6	large freq. zone

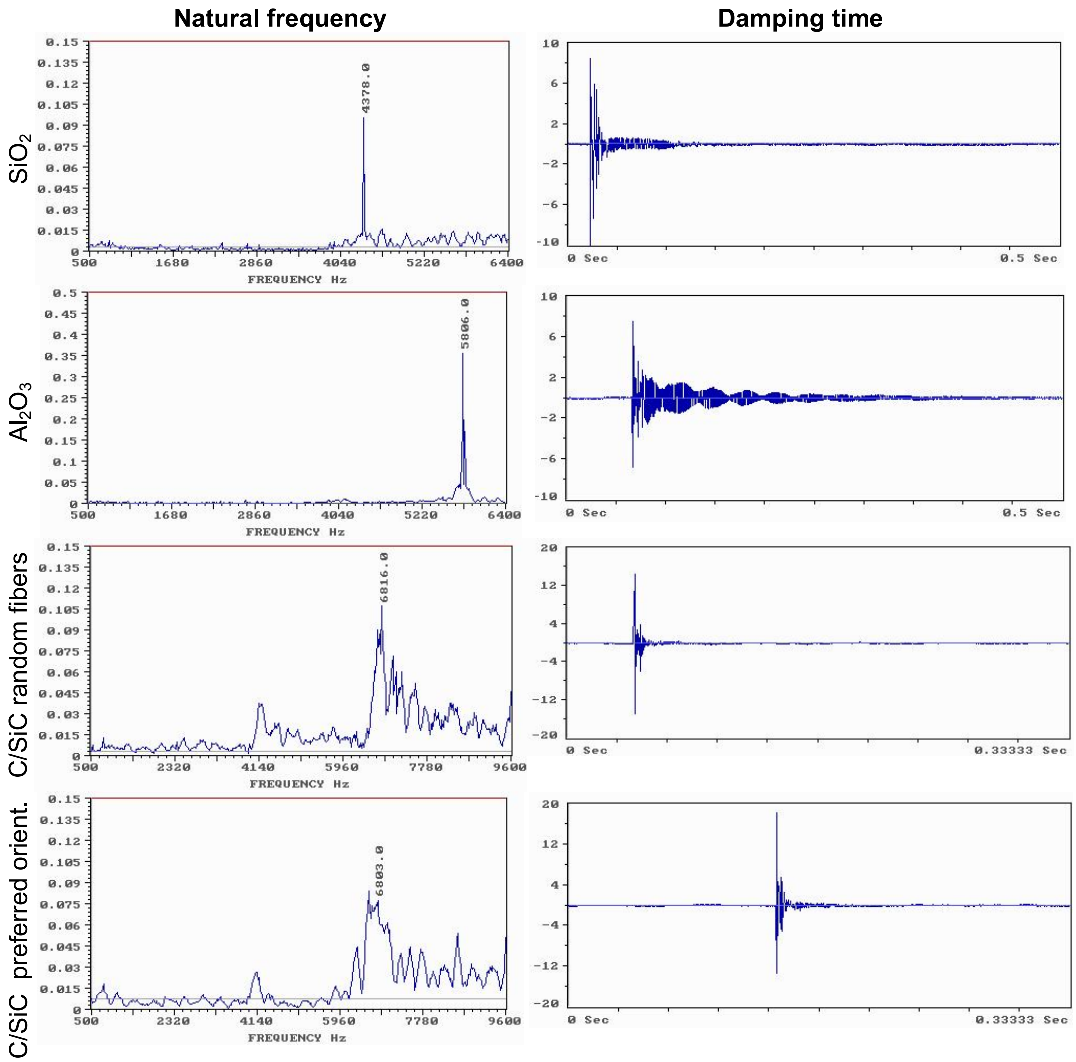

Fig. 8. Natural frequency and damping time

Sample 2: Corundum is oxid ceramics that involves min. 99.7 % Al_2O_3. Some material properties: bending strength min. 300 MPa, Young's module 380-400 GPa, resistance to thermal changes up to 150 K, density min. $3.8x10^3$ kg/m^3.

The samples 3 and 4 are made of ceramics composite C/SiC. SiC (carborundum) belongs to technical non-oxide ceramics branch. SiC are infiltrated by short carbon fibre that improving the mechanical and thermal properties of SiC. Some material properties: Density: 2.65 g/cm^3, Young's module 250-350 GPa, bending strength min. 160-200 MPa. Composite C/SiC comprises short carbon fibres with length of 3 to 6 mm of 12 k thickness (1k=1000 filaments). The samples 3 and 4 have different orientation of fibers in volume. The sample 3 has randomly distributed fibres so the material is considered to be isotropic. The sample 4 has short fibers with preferred orientation perpendicular to pipe axis. The material properties of sample 4 are orthotropic.

Fig. 8 shows narrow and large frequency zones of dynamic response. The dominant natural frequency is not evident for samples 3 and 4. Such property is very suitable for preventing the resonance comparing with samples 1 and 2 that have narrow frequency zone with one dominant natural frequency. Sample 2 has very long damping time. If the non-damped sample would be excited by dynamic force, the vibrations would be larger. One can see that damping time is very short in case of composite material samples 3 and 4. Such materials are very appropriate for designing the components intended for dynamic load with variable exciting frequencies.

The conventional materials have the similar character of properties as samples 1 and 2. The frequency zone is narrow and the damping time is long in comparison to that of samples 3 and 4. The internal material friction is low therefore the damping is the relatively low. If we compare cast iron and steel, the cast iron has the better damping properties. The higher quality of steel provides the lower damping properties. The damping coefficient of steel is 0.001 – 0.008, concrete 0.01 – 0.06, cast iron 0.003 – 0.03. [12] For comparison, damping coefficient of rubber is 0.1 – 0.3 and of glass is 0.0006 – 0.002.

4. DISCUSSION

The radial clearance and accuracy of shaft/cylinder have the main role in dynamic excitation resulting in unwanted vibrations. Additionally, the task of vibrations reduction is solved by use of composite core and/or casing of plate cylinder with special composite material typology and design that allow the low vibrations and improved damping. The printing process is influenced by other factors not only by machine arrangement and use of composite materials. We can conclude that printing quality is influenced mainly by following factors:

- radial clearance of bearings in each printing position,
- complexity (relief – straight edges placement) of printed image,
- sequence of individual printing position corresponding with individual colours,
- material and structure of cylinder cores and casings,
- properties of tint (viscosity),
- material properties of flexible films,
- control of printing pressure between plate and central impression cylinder.

Despite the fact that new advanced flexographic printing machines involve diagnostics of printing quality monitoring, the important role (cca 50%) in flexoprinting is know-how of operating printerman. His main duty is to find maximum printing speed keeping the appropriate quality involving all factors.

The conventional materials (steel, concrete, cast iron etc.) have low inner material friction that causes the low absorption of shock waves caused by vibrations. The experimental testing of samples confirmed differences in dynamic response and useful large frequency zone without dominant natural frequency of fiber composite materials that prevent resonance effect and suit for dynamic excitation.

The experimental testing was confirmed by numerical simulation focused on microscopic representation of shock waves absorption due to inner composite structure involving reinforcing fibers/particles and resulting in suitable change of stress and displacement distribution that do not caused the destruction. The final result is regulation of high kinetic energy propagation.

5. CONCLUSION

The paper described two areas for increasing the production of machines applied to the problem of achievement the higher speed of flexographic printing keeping its quality. The first area involves improving the accuracy of joints, sub-assembles and assembles by their revision, adjustment and correction. The second area involves the usage of the composite materials and structures. The both areas are supported by use of the vibrodiagnostics.

The presented two areas are sources of improving the productivity. They can be applied to various manufacturing machines, not only flexoprinting machines. The improving of components accuracy and component joints, machine arrangement and use of damping composite materials results in sophisticated increasing the productivity of production machine tools.

Outcomes:

- Vibrodiagnostic analysis of flexoprinting process.
- Designing the process of arrangement of flexographic printing machine according to vibration measuring.
- Application of non-conventional material that provided 53% of increasing the printing speed keeping the quality. The printing speed of steel core cylinders with ordinary casing was 150 m/min. The combination of steel core and composite casing allowed 170 - 180 m/min of printing speed and the composite core and casing achieved 220 - 230 m/min. In present, the disadvantage is the price of composite cylinder that is 100% higher comparing to steel.
- Described approaches may be used for other industrial applications.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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