

Original Research Article

Applying vibrodiagnostics control and composite materials for increasing the productivity of production machines

ABSTRACT

The paper presents results of research focused to application based on vibrodiagnostics control and use of composite materials for increasing the productivity of production machines. The application was developed by solving the increase of flexographic printing machine productivity keeping the printing quality and increasing the printing speed. The paper describes the monitoring, evaluating, comparing, applying composite materials to decrease the vibrations and increase the damping of flexographic printing machines. The approach is focused to accuracy of mounting, accuracy of individual machine parts in component joints and modal properties of components made from non-conventional materials.

Keywords: vibrodiagnostics control, composite cylinder, printing speed, damping

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 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.

The main requirement of 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 problem solving methodology that is appropriate for other production machines problems based on large vibrations.

2. 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:

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

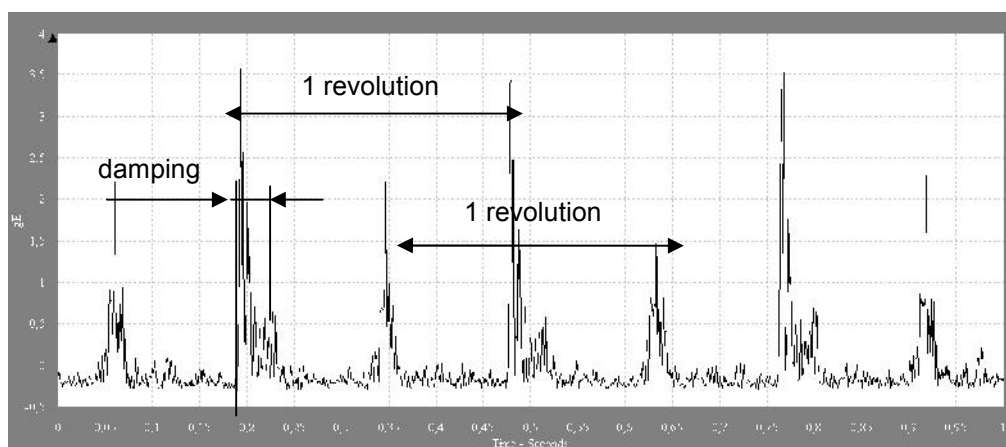
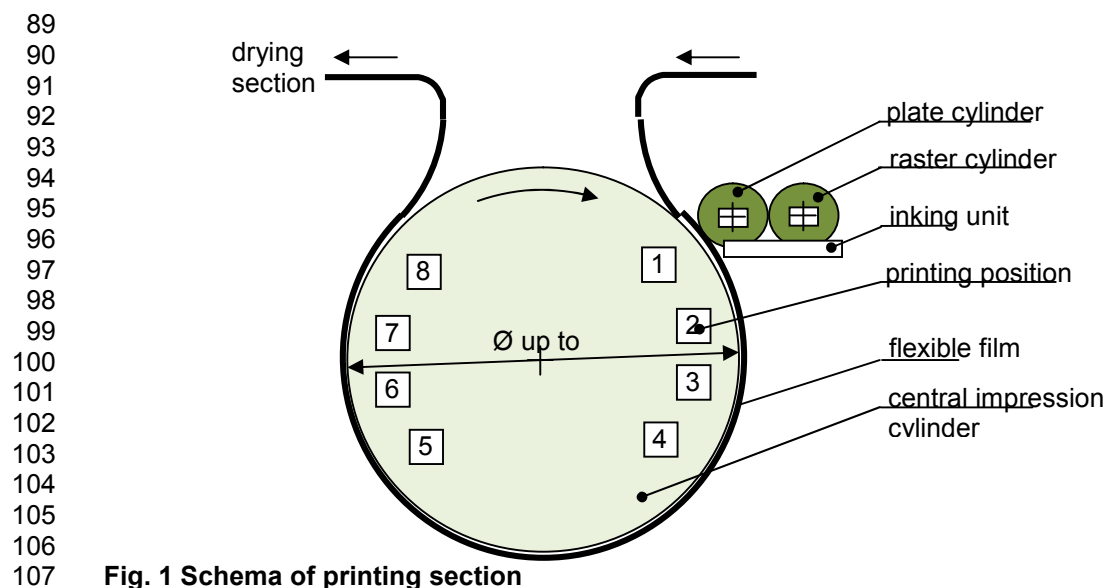
where $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ is matrix of weight, damping and stiffness of mechanical system of $n \times n$ dimension, $\mathbf{F}$ is vector of load (excitation forces), $\mathbf{q}$, $\dot{\mathbf{q}}$, $\ddot{\mathbf{q}}$ is vector of displacements (linear and angular), velocities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

2.1 Printing process description

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).

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 solid of revolution. [5, 9]



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

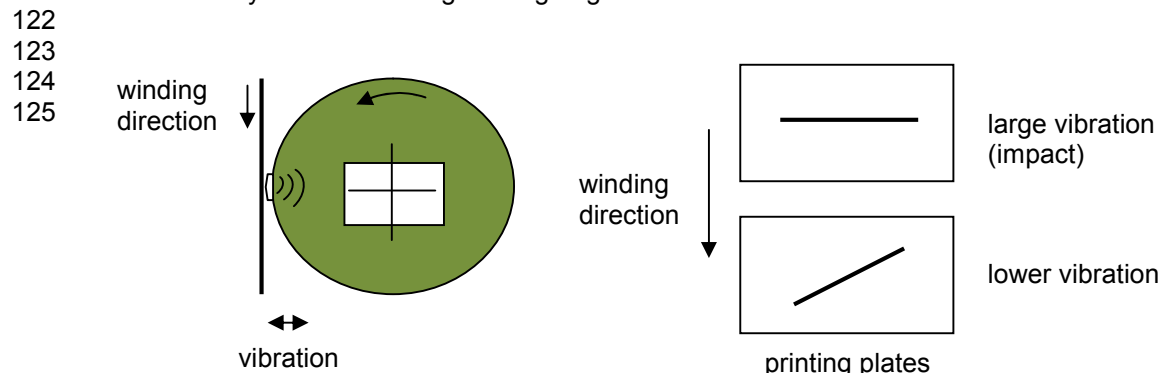


Fig. 3 Vibration source and location of edges at printing plates

The magnitude of vibrations is influenced by material of plate situated on plate cylinder. The plates are made of four finds 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 sources 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.

3. VIBRATIONS AND COMPONENT JOINTS ACCURACY

The next section will describe 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. [3, 11] 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 bearing. The optimal function of needle bearing is guaranteed by producer in case of recommended radial clearance in range 30 – 50 μm .

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

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 norm STN ISO 10816-3: Measuring of vibrations of non-revolving parts on revolving machines. Table 2 introduces the recommended limits of Warning and Danger of summing vibrations according to mentioned norm.

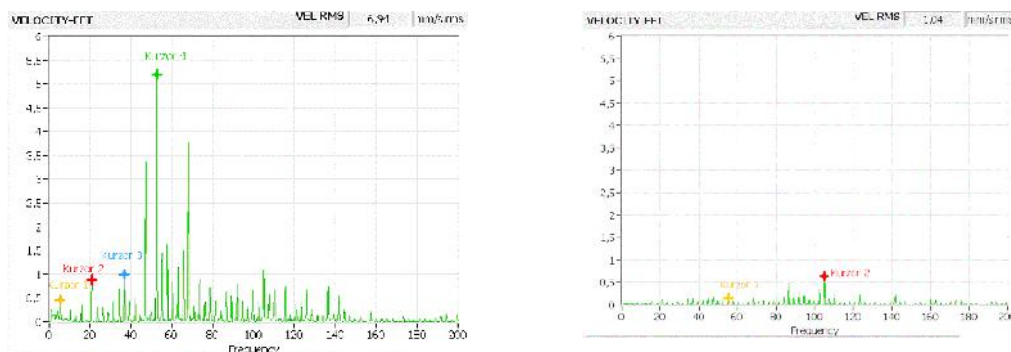
Table 2. Alarms limits and measured values before and after arrangement work (assortment X)

			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
	position 8	VD	1.78	0.15	2.0	
	DS	HD	6.94	0.28	2.2	
	position 8	VD	1.56	0.10	1.8	
after	OS	HD	1.32	0.10	1.4	No alarm
	position 8	VD	1.00	0.10	1.2	
	DS	HD	1.04	0.08	0.8	
	position 8	VD	0.59	0.09	1.0	

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, e.g. 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 decreasing of dynamic excitation of printing position appeared that result in increasing the quality of printing.

Fig. 4 shows the FFT spectrums (up) and Time records (down) before and after arrangement of printing position 8.



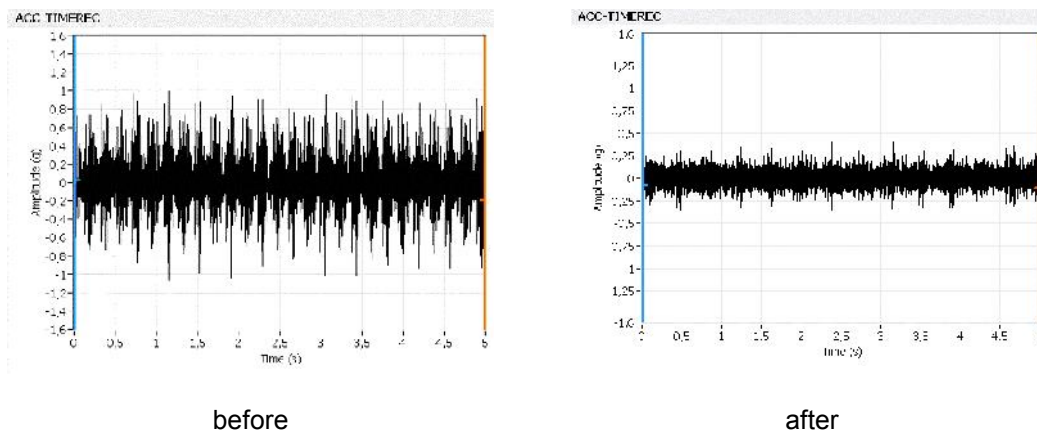


Fig. 4 Printing position 8

4. USE OF COMPOSITE MATERIALS AND STRUCTURES

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

The macroscopic dynamic response of structures is important in engineering applications depending on microscopic material structure. [2, 6] The waves propagate through individual machine tool components that form 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 inhomogenities (pores, impurities, etc.) that are source of material damping. The different materials in composite materials considerably change the wave propagation and material damping. The typology of non-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 effect 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. [4, 7] 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 [8]: 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:

228

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

229

230

231

232

233

234

235

236

237

238

239

240

241

242

243

244

245

246

247

248

249

250

251

252

253

254

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.

The structure with complex shape involves each mentioned basic waves. The fibres/non-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 inhomogenities. 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 source 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.

4.1 Printing machine application

255

256

257

258

259

260

Despite the described arrangement work in chapter 3 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.

261

262

263

264

265

In ordinary, the plate cylinders consist of core and casing (Fig. 5). The different material combinations can be used:

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

266

267

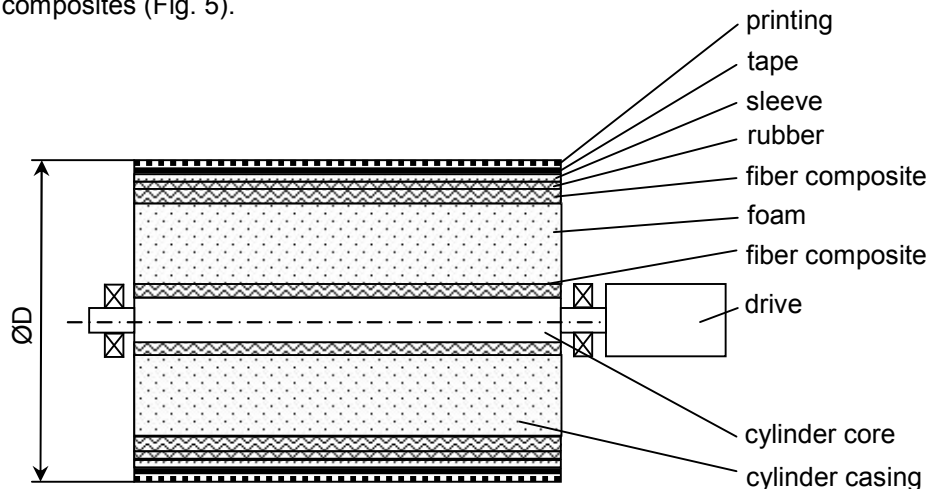
268

269

270

271

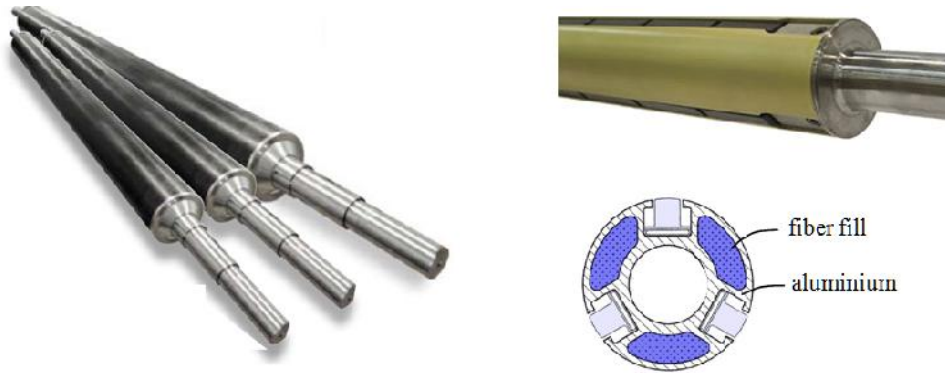
The composite casings consists of multilayer sandwich, composite cores are made of fibre composites (Fig. 5).



272
273
274
275
276
277
278

Fig. 5 Multilayered sandwich plate cylinder

279 The various producers of composite printing cylinders differentiate by inner structure and
280 material of cylinder (Fig. 6).
281



282
283

Fig. 6 Composite carbon cores of cylinders

284 The left situated cylinders in Fig. 6 consist of winded high/super-high module carbon fibres.
285 The cylinder on the right side has aluminum profile with filling of fibers oriented in one
286 direction that increases the stiffening effect. The producer of such cylinders notifies
287 increasing of printing speed up to 200%. The research and development in filled of
288 advanced applications of composite materials is in progress.

289
290 One of many advantages of the composite cylinders is its minimal deflection regarding the
291 high cylinder stiffness. The Young's module of composite cylinders is about 400 GPa. The
292 vibrations have decreased values. Moreover, due to inner cylinder and material structure the
293 damping time is shortened. Further, composite cylinders have low weight and need less
294 energy to drive. They are called superlight comparing with steel cylinders. This is important
295 factor in economy of application.

296
297 Our application provided 53 % of increasing the printing speed. While the printing speed of
298 steel core cylinder with ordinary casing was 150 m/min, the combination steel core –
299 composite casing allowed 170 - 180 m/min of printing speed and the composite core and
300 casing achieved 220 - 230 m/min. In present the price of composite cylinder is 100% higher.

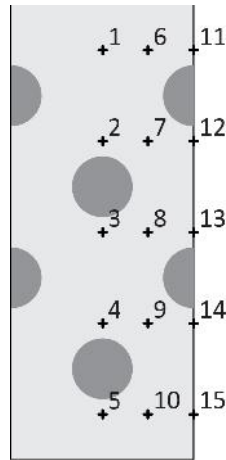
301

302 4.2 Numerical simulation of wave propagation

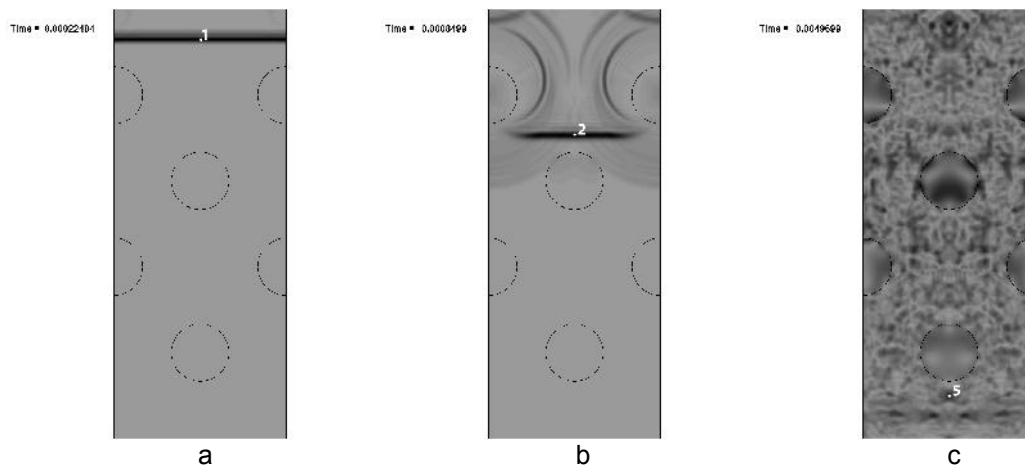
303

304 The presented numerical simulation of material damping in microscopic level concerns 2D
305 numerical model (plain strain), Fig. 7, with reinforcing straight fibers/particles that are much
306 stiffer than matrix. It presents partial result of research project (more in [1, 12]). The LS
307 DYNA model involves straight fibers/particles of R1 radius situated in layers parallel to
308 surface with distance $\Delta_1=\Delta_2=3R$ between each other. The ratio of Young's modules matrix
309 and fiber $E_m:E_f$ is 1:100. The load of shock wave raising in time $0.05\mu s$ from 0 up to 31.5

310 MPa and backward in same time it falls to 0. The following simulation acknowledges and
 311 document significant damping effect in materials reinforced by fibers/particles.
 312



313
 314 **Fig. 7 2D model of reinforced composite**



315 **Fig. 8 Effective stress distribution passing the points (1, 2, 5)**

316 Initially, the shock propagates without any defect (Fig. 8a). Passing the first layer of
 317 fibers/particles, the reflection and interference appears (Fig. 8b). Passing the all fiber layers,
 318 the dispersed shock wave is evident (Fig. 8c).
 319

320 Table 3 summarizes results of average stress in layers of model defined by individual points
 321 showed in Fig. 7. The notable decrease of stress is visible due to interaction of shock waves
 322 and fibers/particles. The damping is obtained purely by absorption, reflection and
 323 interference of waves with fibers/particles. The decrease of values concerns also
 324 displacements.
 325

326 **Table 3. Average stress in layers under surface**
 327

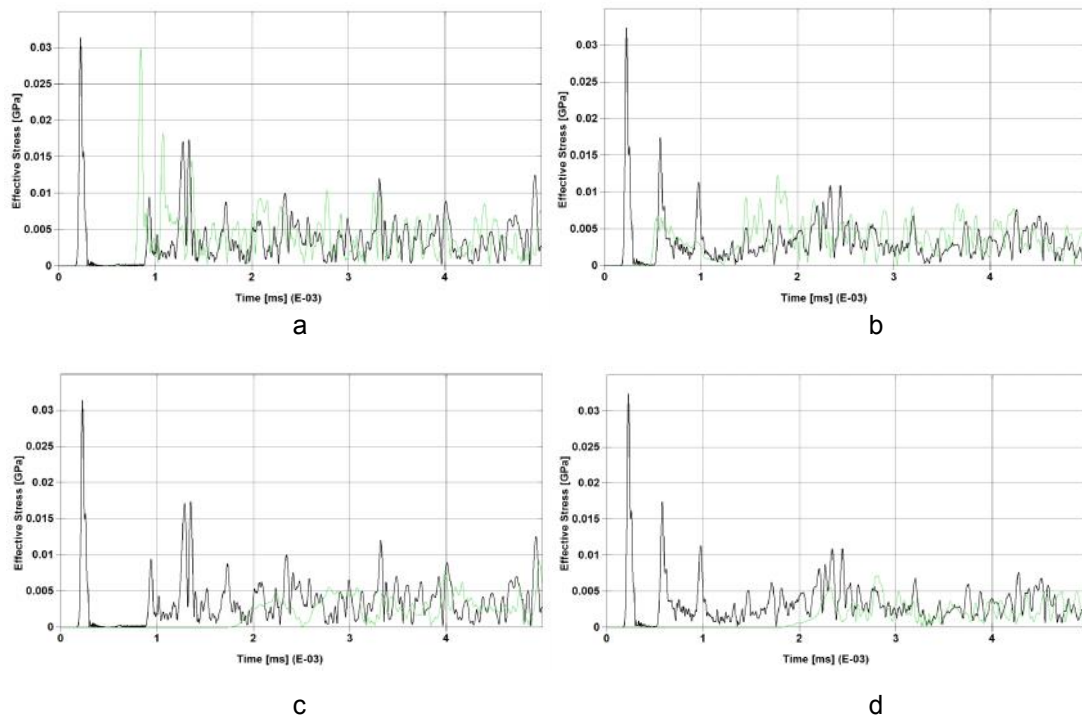
Layer through points	Stress [MPa]
1-6-11	42.54
2-7-12	30.31

3-8-13	16.33
4-9-14	11.73
5-10-15	9.04

328

329 Fig 9 provides comparison of effective stress distribution regarding the time and position of
 330 individual points 1-15. The black curves are for point closer to surface and the green one is
 331 for other point.

332
 333



334
 335

336 **Fig. 9 Effective stress in points 1 and 2 (a), 11 and 12 (b), 1 and 5 (c), 11 and 15 (d)**

337

338 4.3 Experimental testing of dynamic properties

339

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

346

347 The tested samples were pipes with dimensions: outer diameter $D=12\text{mm}$, inner diameter
 348 $d=8\text{mm}$, length $l=110\text{mm}$. The samples were made of glass (SiO_2), oxide ceramics
 349 (corundum Al_2O_3) and composite of ceramics matrix with short fibers of carbon (C/SiC). The
 350 measured values are in Table 4 and Fig. 10.

351

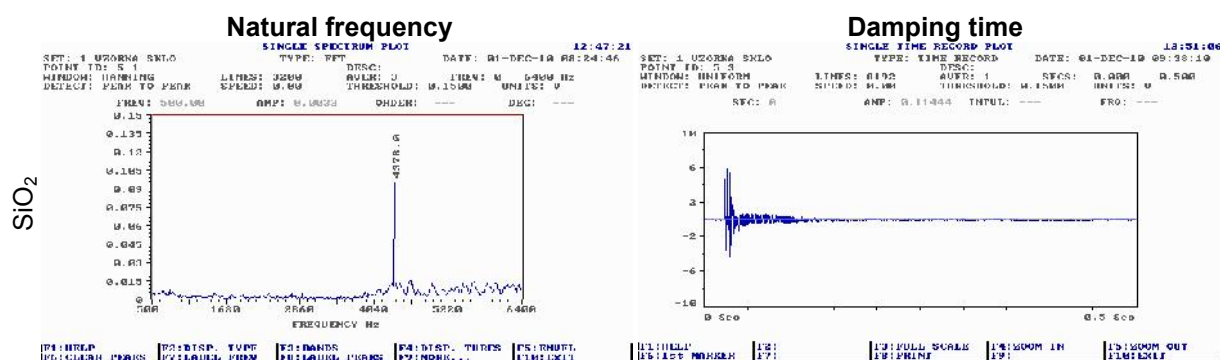
352 **Table 4. Measured values**

353

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 ₂ O 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

Sample 1: Glass SiO₂ is homogenous, amorphous, isotropic, solid and brittle material in metastable state. It involves mostly siliceous sand, soda, oxides of alkali metals, calcite. Some material properties: tensile strength 33 MPa, density 2.53 g/cm³. Sample 2: Corundum is oxid ceramics that involves min. 99.7 % Al₂O₃. Some material properties: bending strength min. 300 MPa, Young's module 380-400 GPa, resistance to thermal changes up to 150 K, density min. 3.8x10³ kg/m³. 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/cm³, Young's module 250-350 GPa, bending strength min. 160-200 MPa. Composite SiC comprises short carbon fibres with length of 3 to 6 mm of 12k thickness (1k=1000filaments). The samples 3 and 4 have different orientation of fibers in volume. The sample 3 has randomly distributed fibres so the material is considered as isotropic. The sample 4 has short fibers with preferred orientation perpendicular to pipe axis. The material properties of sample 4 are orthotropic.

Fig. 10 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 is excited by dynamic force, the vibrations are 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 frequency. The mentioned samples are different for their microstructure so material properties of sample 4 are directional.



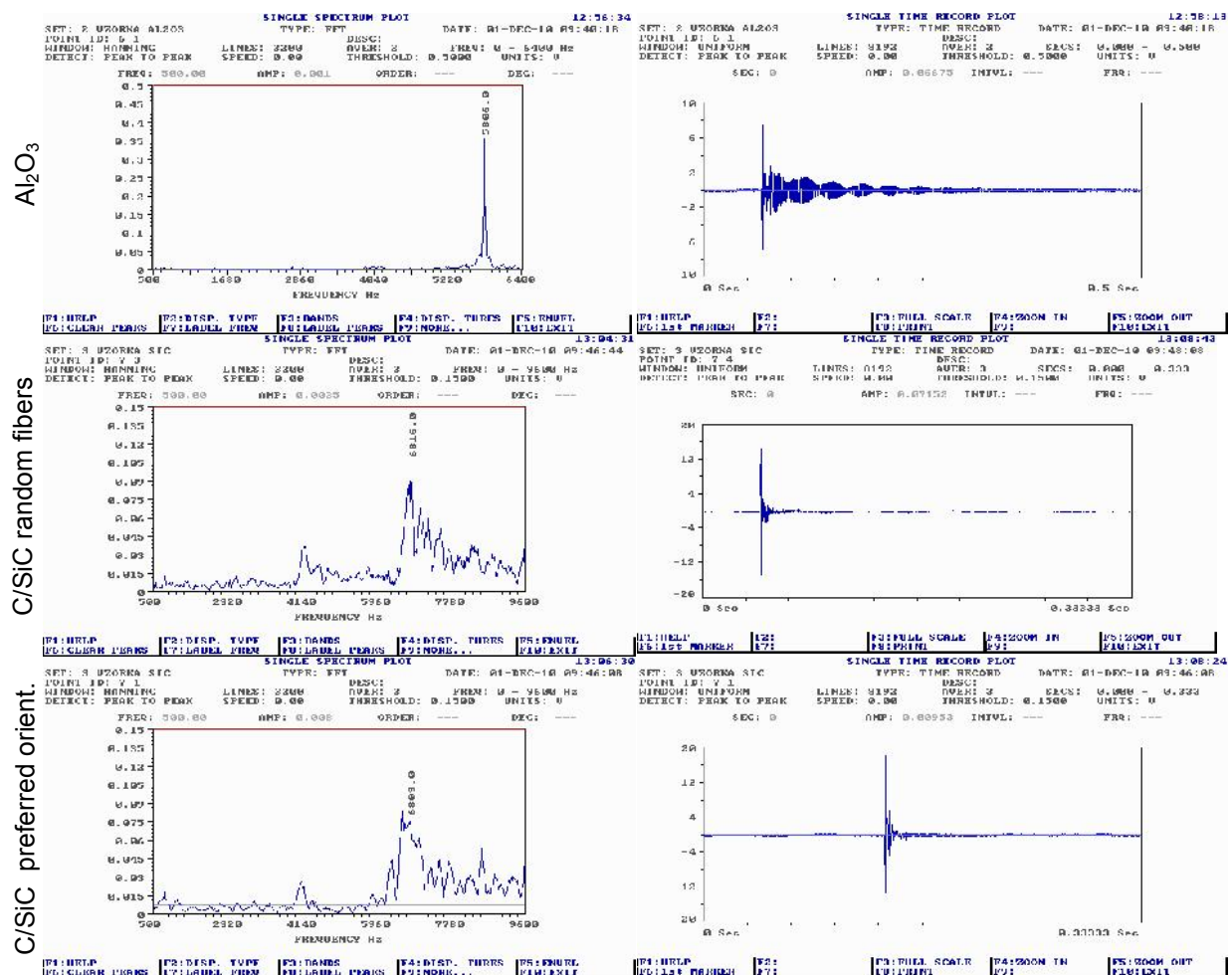


Fig. 10 Natural frequency and damping time

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 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. [10] For comparison, damping coefficient of rubber is 0.1-0.3 and of glass is 0.0006-0.002.

5. DISCUSSION AND CONCLUSIONS

The paper describes two areas of methodology for increasing the production of machines - vibrodiagnostics control and improving the accuracy and use of composite materials and structures - for solving the problem of achievement the higher quality of printing and higher speed of flexographic printing of packaging films.

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,
- sequentiality 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.

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

REFERENCES

1. P. Droppa, M. Vančo, V. Ferencey: Response of structure to ballistic load, *Advances in Military Technology*. 2012; 7 (2): 93 – 110.
2. V. Kompiš and Z. Murčinková, Thermal Properties of Short Fibre Composites Modeled by Meshless Method, *Advances in Material Science and Engineering*, Hindawi. 2014: 1 - 8.
3. K. Monková K. and A. Šmeringaiová, Dynamic analysis of gears, In: *Recent*. 2011; 12 (3): 331-334.
4. J. Murčinko and Z. Murčinková, Implementation of intelligent elements in vibration diagnostics of CNC machines, *Applied Mechanics and Materials*. 2013; 308: 87-93.
5. J. Murčinko and Z. Murčinková, On-line monitoring system applied to explosive conditions of printing machine dryers, *Risk Analysis*. 2012; 44 (8): 305-316.
6. Z. Murčinková, Material damping of fibrous composites for devices driven by artificial muscles, *Applied Mechanics and Materials*. 2014; 460: 33-40.

- 453 7. Z. Murčinková and J. Murčinko, Monitoring of processes in component joints by
454 intelligent system, ICSSE 2013 - IEEE International Conference on System Science and
455 Engineering, Proceedings, Óbuda university, Budapest. 2013: 325-328.
- 456 8. J. W. Palm, Modeling, Analysis and Control of Dynamic Systems, 2nd Ed., John Wiley &
457 Sons, Inc., New York, USA 2000.
- 458 9. S. Šoltésová and P. Baron, The operation monitoring condition of the production
459 machinery and facilities using the tools of technical diagnostics, Applied Mechanics and
460 Materials. 2013; 308: 105-109.
- 461 10. K. Vasilko, Deformation structures and tool wear during high-speed machining, In:
462 Technologické inžinierstvo. 2013; 10 (1): 12-16.
- 463 11. I. Vojtko, M. Kočiško and A. Šmeringaiová, Vibration of worm gear boxes, Applied
464 Mechanics and Materials. 2013; 308: 45-49.
- 465 12. M. Žmindák and M. Dudinský, Computational modelling of composite materials
466 reinforced by glass fibers, Procedia Engineering. 2012; 48: 701-710.