ISSN 1392-1134/ eISSN 2345-0371
AGRICULTURAL ENGINEERING
2021, Vol. 53, 47-54 p.
https://doi.org/10.15544/ageng.2021.53.9

MEASUREMENT OF VIBRATIONS OF AGRICULTURAL MACHINES BY USING MOIRE METHODS

***Kazimieras Ragulskis*[*], *Rimas Maskeliūnas*[**], *Arvydas Pauliukas*[***], *Petras Paškevičius*[****], *Algimantas Bubulis*[*], *Anatolii Korpach*[*****], *Liutauras Ragulskis*[***]**
[*]Kaunas University of Technology, Kaunas, Lithuania
[**]Vilnius Gediminas Technical University, Vilnius, Lithuania
[***]Vytautas Magnus University, Kaunas, Lithuania
[****]Company "Vaivora", Kaunas, Lithuania
[*****]National Transport University, Kyiv, Ukraine

Abstract

This paper is a full article on the basis of the material presented in the two conference thesis. In the process of investigation of dynamics and vibrations of agricultural machines various experimental methods are used. Among them moiré methods can be noted because of their simplicity and easy applicability. Projection moiré is most often used for this purpose. It is used to visually estimate the shape of the eigenmode by projecting moire grating to a flat part of the case of the agricultural machine. Time averaging is applied when investigating vibrations of the structure according to the eigenmode. In this paper possibilities of application of hybrid experimental – numerical procedures for measurements of large amplitude vibrations by reflection moiré are investigated.

Keywords: *elastic structure, hybrid experimental – numerical procedures, large amplitude vibrations, time averaged moiré, reflection moiré.*

Received 2021-05-19, accepted 2021-11-15

1. Introduction

This paper is a full article on the basis of the material presented in the two conference thesis: (Ragulskis K. *et al.*, 2020) and (Ragulskis K. *et al.*, 2021).

In the process of investigation of dynamics and vibrations of agricultural machines various experimental methods are used. Among them moiré methods can be noted because of their simplicity and easy applicability. Projection moiré is most often used for this purpose. It is used to visually estimate the shape of the eigenmode by projecting moire grating to a flat part of the case of the agricultural machine. Time averaging is applied when investigating vibrations of the structure according to the eigenmode.

In this paper possibilities of application of hybrid experimental – numerical procedures for measurements of large amplitude vibrations by reflection moiré are investigated. This paper is the continuation of investigations of the authors presented in (Maskeliūnas R. *et al.*, 2021) and (Maskeliūnas R. *et al.*, 2019).

In the previous papers typical results when vibrations are considered of large amplitude for a given shape of eigenmode were described and compared with the results when vibrations are considered as being of small amplitude. Here the shape of the eigenmode is determined numerically on the basis of a finite element model and thus the obtained results are applicable in hybrid experimental – numerical procedures.

Interpretation of experimental time averaged reflection moiré images for small amplitude vibrations is described in (Ragulskis M. *et al.*, 2006). Related problems are investigated in (Ragulskis K. *et al.*, 2006), (Maskeliūnas V. *et al.*, 2018), (Maskeliūnas V. *et al.*, 2016), (Maskeliūnas R. *et al.*, 2016), (Maskeliūnas R., Ragulskis K., Paškevičius P., Pauliukas A. *et al.*, 2015), (Maskeliūnas R., Ragulskis K., Paškevičius P., Patašienė L. *et al.*, 2015), (Ragulskis M. *et al.*, 2005), (Ragulskis M. *et al.*, 2002), (Saunorienė L., Ragulskis M., 2010), (Soifer V. A., 2001), (Timoshenko S. P., Goodier J. N., 1975), (Vest C., 1982) and in a number of other research papers.

First model for the analysis of time averaged reflection moiré measurement of large amplitude vibrations is described. Then results of analysis of time averaged reflection moiré measurement of large amplitude vibrations are presented, which include eigenmodes of the structure as well as investigation of intensities of time averaged reflection moiré images.

2. Model for the analysis of time averaged reflection moiré measurement of large amplitude vibrations

Investigation is based on a plane strain problem. Further *x* and *y* denote the axes of coordinates, *u* and *v* denote displacements in the directions of the *x* and *y* axes.

The stiffness matrix is of the following form:

$$[K]=\int[B]^T[D][B]dxdy, \tag{1}$$

where:

$$[B]=\begin{bmatrix}\frac{\partial N_1}{\partial x} & 0 & \dots\\ 0 & \frac{\partial N_1}{\partial y} & \dots\\ \frac{\partial N_1}{\partial y} & \frac{\partial N_1}{\partial x} & \dots\end{bmatrix},\ [D]=\begin{bmatrix}K+\frac{4}{3}G & K-\frac{2}{3}G & 0\\ K-\frac{2}{3}G & K+\frac{4}{3}G & 0\\ 0 & 0 & G\end{bmatrix}, \tag{2}$$

where N_1, N_2, … denote the shape functions of the finite element, $K=\frac{E}{3(1-2\nu)}$, $G=\frac{E}{2(1+\nu)}$, where E is the modulus of elasticity and ν is the Poisson's ratio.

The mass matrix is of the following form:

$$[M]=\int[N]^T\rho[N]dxdy, \tag{3}$$

where ρ denotes the density of material of the structure and also:

$$[N]=\begin{bmatrix}N_1 & 0 & \dots\\ 0 & N_1 & \dots\end{bmatrix}. \tag{4}$$

The investigated eigenmode further is denoted as $\{\delta\}$. It is necessary to determine nodal values of the derivative $\frac{\partial v}{\partial x}$. For this purpose it is necessary to solve the system of linear algebraic equations:

$$[\bar{K}]\{\bar{\delta}\}=\{\bar{F}\}, \tag{5}$$

where the matrix of the system has the following form:

$$[\bar{K}]=\int[\bar{N}]^T[\bar{N}]dxdy, \tag{6}$$

where:

$$[\bar{N}]=[N_1\quad \dots], \tag{7}$$

also where $\{\bar{\delta}\}$ is the vector of the nodal values of $\frac{\partial v}{\partial x}$ and where:

$$\{\bar{F}\} = \int [\bar{N}]^T \frac{\partial v}{\partial x} dxdy, \tag{8}$$

where it is assumed that:

$$\frac{\partial v}{\partial x} = [\bar{B}]\{\delta\}, \tag{9}$$

where:

$$[\bar{B}] = \begin{bmatrix} 0 & \frac{\partial N_1}{\partial x} & \dots \end{bmatrix}. \tag{10}$$

Intensity of the time averaged reflection moiré image is calculated on the straight upper surface of the structure. It is assumed that moiré grating and the photographic plate are parallel to the surface of the structure. The distance between them and the surface of the structure in the status of equilibrium is assumed equal to *d*.

Intensity of the time averaged reflection moiré image is calculated as:

$$I = \frac{1}{m}\sum_{i=1}^{m}\cos^2\frac{2\pi}{\lambda}\left(x - 2d\frac{\partial v}{\partial x}\sin 2\pi\frac{i-1}{m}\right), \tag{11}$$

where *m* is a large integer number and λ determines the width of moiré lines.

For vibrations having large amplitude intensity of the time averaged reflection moiré image is calculated as:

$$I = \frac{1}{m}\sum_{i=1}^{m}\cos^2\frac{2\pi}{\lambda}\left(x - 2\left(d - v\sin 2\pi\frac{i-1}{m}\right)\frac{\partial v}{\partial x}\sin 2\pi\frac{i-1}{m}\right). \tag{12}$$

Intensity is represented graphically in the normal direction to the straight upper surface of the structure.

3. Results of analysis of time averaged reflection moiré measurement of large amplitude vibrations

The elastic structure consists of one row of two dimensional Lagrange quadratic finite elements. All displacements of the three nodes on the left end of the investigated structure are assumed equal to zero.

The following values of parameters of the investigated structure are assumed: modulus of elasticity $E = 6\cdot 10^8$ Pa, Poisson's ratio $\nu = 0.3$, density of the material $\rho = 785\ \frac{\mathrm{kg}}{\mathrm{m}^3}$.

Further the first two eigenmodes are investigated. First the eigenmodes are presented in detail and then variation of intensity on the straight upper surface of the structure is analysed.

3.1. Eigenmodes of the structure

External boundaries of the finite element mesh of the structure deflected according to the first eigenmode are presented in Fig. 1.

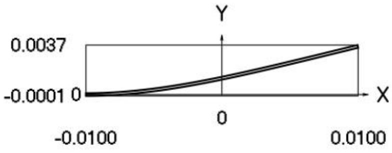


Fig. 1. The first eigenmode

External boundaries of the finite element mesh of the structure deflected according to the second eigenmode are presented in Fig. 2.

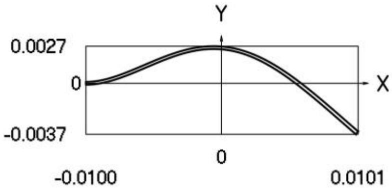
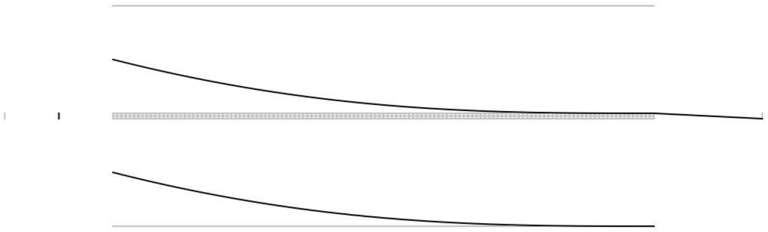
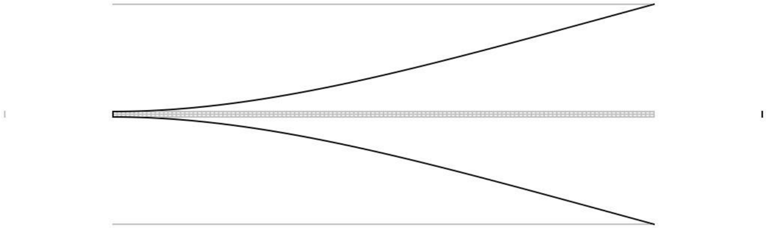


Fig. 2. The second eigenmode

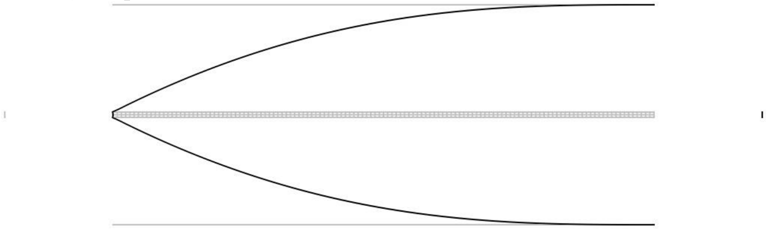
Displacement *u* on the external boundaries of the finite element mesh of the structure for the first eigenmode is presented in Fig. 3a. Displacement *v* on the external boundaries of the finite element mesh of the structure for the first eigenmode is presented in Fig. 3b. Derivative $\frac{\partial v}{\partial x}$ on the external boundaries of the finite element mesh of the structure for the first eigenmode is presented in Fig. 3c.



a) Displacement *u* on the external boundaries of the structure



b) Displacement *v* on the external boundaries of the structure



c) Derivative $\frac{\partial v}{\partial x}$ on the external boundaries of the structure

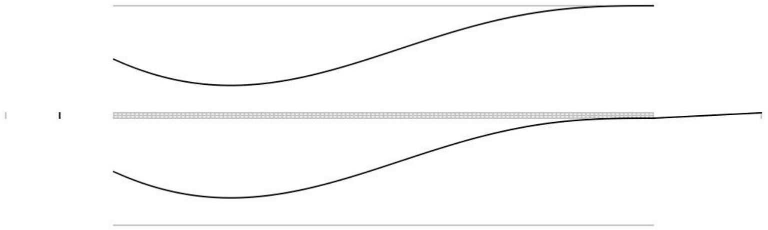
Fig. 3. Investigation of the first eigenmode

Minimum and maximum values of the represented quantities for the first eigenmode are presented in Table 1.

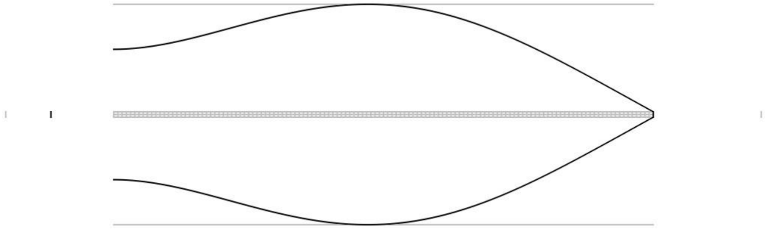
Table 1. Minimum and maximum values for the first eigenmode

	Minimum	Maximum
u	-0.245765	0.245765
v	0	35.697
$\frac{\partial v}{\partial x}$	-3.40917	2457.66

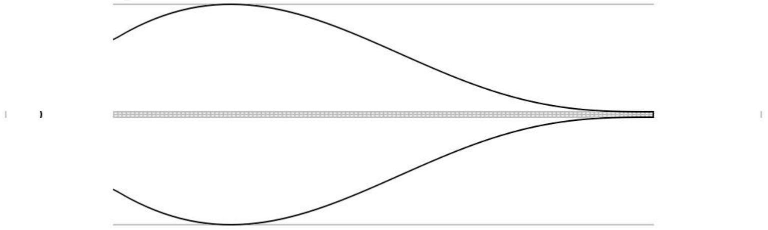
Displacement u on the external boundaries of the finite element mesh of the structure for the second eigenmode is presented in Fig. 4a. Displacement v on the external boundaries of the finite element mesh of the structure for the second eigenmode is presented in Fig. 4b. Derivative $\frac{\partial v}{\partial x}$ on the external boundaries of the finite element mesh of the structure for the second eigenmode is presented in Fig. 4c.



a) Displacement u on the external boundaries of the structure



b) Displacement v on the external boundaries of the structure



c) Derivative $\frac{\partial v}{\partial x}$ on the external boundaries of the structure

Fig. 4. Investigation of the second eigenmode

Minimum and maximum values of the represented quantities for the second eigenmode are presented in Table 2.

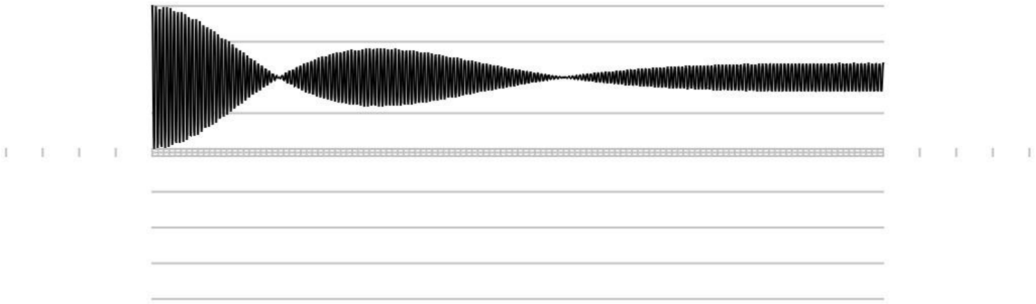
Table 2. Minimum and maximum values for the second eigenmode

	Minimum	Maximum
u	-0.85323	0.85323
v	-35.6866	25.7064
$\frac{\partial v}{\partial x}$	-8532.47	4173.9

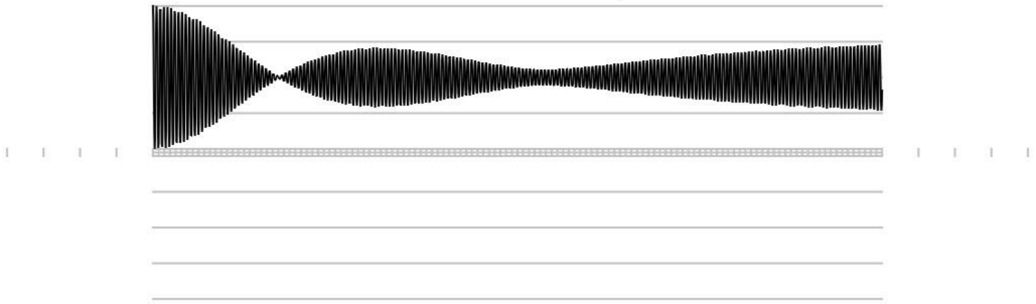
3.2. Investigation of intensities of time averaged reflection moiré images

Intensity of the time averaged reflection moiré image on the straight upper surface of the structure is investigated.

Results for the first eigenmode when vibrations are considered to be of small amplitude are shown in Fig. 5a and when vibrations are considered to be of large amplitude they are shown in Fig. 5b.



a) Vibrations of small amplitude

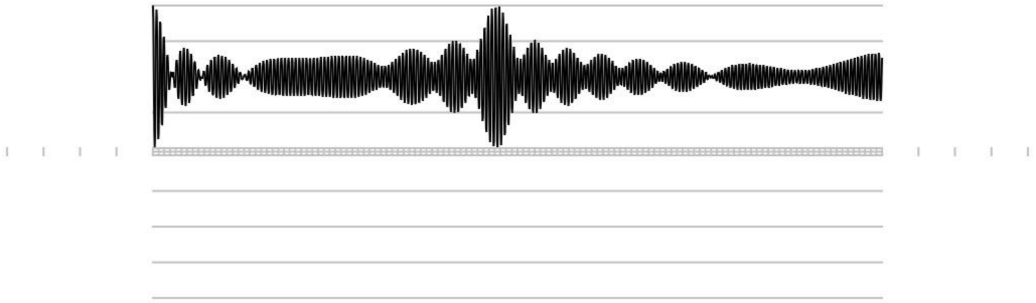


b) Vibrations of large amplitude

Fig. 5. Intensities of time averaged reflection moiré images for the first eigenmode

Results for the second eigenmode when vibrations are considered to be of small amplitude are shown in Fig. 6a and when vibrations are considered to be of large amplitude they are shown in Fig. 6b.

a) Vibrations of small amplitude



b) Vibrations of large amplitude

Fig. 6. Intensities of time averaged reflection moiré images for the second eigenmode

The presented results are applicable in hybrid experimental – numerical procedures for interpretation of experimental time averaged reflection moire images.

For the problem of investigation of small amplitude vibrations, that is when it is assumed that the distance between the moiré grating and the photographic plate to the surface of the structure in the status of equilibrium is much larger than the deflection of the structure, interpretation of experimental time averaged reflection moiré images is described in detail in (Ragulskis M. *et al.*, 2006). This interpretation can be used for estimation of amplitudes of deflections of the investigated elastic structure performing vibrations according to the eigenmode.

From the results represented in the obtained Figures one can see that the results when vibrations are considered to be of large amplitude exhibit some difference from the obtained results when vibrations are of small amplitude. It is seen that this difference is greatest where the amplitudes of vibrations are large.

But the procedure of direct interpretation of experimental results for the structure performing vibrations that are of large amplitude is not as simple as for the case when vibrations are considered to be of small amplitude. Thus the procedure presented in this paper indicates the possibilities of application of hybrid experimental – numerical approach for interpretation of experimental results for the problem when vibrations are considered to be of large amplitude.

4. Conclusions

In the process of investigation of dynamics and vibrations of agricultural machines various experimental methods are used. Among them moiré methods can be noted because of their simplicity and easy applicability. Projection moiré is most often used for this purpose. It is used to visually estimate the shape of the eigenmode by projecting moire grating to a flat part of the case of the agricultural machine. Time averaging is applied when investigating vibrations of the structure according to the eigenmode.

Procedures for measurements of large amplitude vibrations by time averaged reflection moiré are investigated in this paper. The shape of the eigenmode is determined numerically on the basis of a finite element model and thus the obtained results are applicable in hybrid experimental – numerical procedures performing the interpretation of experimental time averaged reflection moire images. The presented results show the importance of use of more precise equation for estimation of intensity of time averaged reflection moiré images when vibrations are of large amplitude.

For the problem of investigation of small amplitude vibrations, that is when it is assumed that the distance between the moiré grating and the photographic plate to the surface of the structure in the status of equilibrium is much larger than the deflection of the structure, interpretation of experimental time averaged reflection moiré images is not a problem. This interpretation can be used for estimation of amplitudes of deflections of the investigated elastic structure performing vibrations according to the eigenmode.

From the obtained results one can see that the results when vibrations are considered to be of large amplitude, they exhibit some difference from the obtained results when vibrations are of small amplitude. It is seen that this difference is greatest where the amplitudes of vibrations are large.

But the procedure of direct interpretation of experimental results for the structure performing vibrations that are of large amplitude is not as simple as for the case when vibrations are considered to be of small amplitude. Thus the procedure presented in this paper indicates the possibilities of application of hybrid experimental – numerical approach for interpretation of experimental results for the problem when vibrations are considered to be of large amplitude.

References

[1] V. Maskeliūnas, R. Maskeliūnas, P. Paškevičius, L. Ragulskis. Measurement of vibrations of a wing. *Journal of Measurements in Engineering,* 2016, 4(3), 183-187 p. **DOI:** https://doi.org/10.21595/jme.2016.17772.

[2] V. Maskeliūnas, R. Maskeliūnas, K. Ragulskis, P. Paškevičius, L. Ragulskis. Reflection moiré for the measurement of wing vibrations. *Journal of Measurements in Engineering,* 2018, 6(2), 100-106 p. **DOI:** https://doi.org/10.21595/jme.2018.20002.

[3] R. Maskeliūnas, K. Ragulskis, P. Paškevičius, L. Patašienė, A. Pauliukas, L. Ragulskis. Measurement of plane vibrations of a two dimensional elastic structure. *Journal of Measurements in Engineering,* 2015, 3(2), 42-47 p.

[4] R. Maskeliūnas, K. Ragulskis, P. Paškevičius, L. Patašienė, L. Ragulskis. Superimposed moiré measurements of vibrations of circular structures. *Journal of Measurements in Engineering,* 2016, 4(1), 15-22 p.

[5] R. Maskeliūnas, K. Ragulskis, P. Paškevičius, A. Pauliukas, L. Ragulskis. Selection of number of gaps in superimposed moiré measurements. *Journal of Measurements in Engineering*, 2015, 3(4), 138-144 p.

[6] R. Maskeliūnas, K. Ragulskis, A. Pauliukas, P. Paškevičius, A. Bubulis, V. Kuzhel, L. Ragulskis. Investigation of measurement of large amplitude vibrations by using the method of reflection moire. *Agricultural Engineering*, 2021, 53, 1-7 p. **DOI:** https://doi.org/10.15544/ageng.2021.53.1.

[7] R. Maskeliūnas; K. Ragulskis; A. Pauliukas; P. Paškevičius; A. Bubulis; L. Ragulskis, 2019. Reflection moire for the measurement of large amplitude vibrations. *Modern Technologies and Prospects of Development of Motor Transport, XII International Scientific Practical Conference, Vinnytsia National Technical University*, Vinnytsia, 116-118 p.

[8] K. Ragulskis; R. Maskeliūnas; A. Pauliukas; P. Paškevičius; A. Bubulis; L. Ragulskis, 2020. Investigation of vibrations of agricultural machines by moire methods. *LXXVI наукова конференція професорсько-викладацького складу, аспірантів, студентів та співробітників відокремлених структурних підрозділів університету, Тези доповідей, Національний транспортний університет,* Kiev, 54 p.

[9] K. Ragulskis; R. Maskeliūnas; A. Pauliukas; P. Paškevičius; L. Ragulskis, 2021. Hybrid experimental – numerical procedures for measurement of vibrations by reflection moire. *LXXVII наукова конференція професорсько-викладацького складу, аспірантів, студентів та співробітників відокремлених структурних підрозділів університету, Тези доповідей, Національний транспортний університет,* Kiev, 47 p.

[10] M. Ragulskis, R. Maskeliūnas, L. Ragulskis, V. Turla. Investigation of dynamic displacements of lithographic press rubber roller by time average geometric moire. *Optics and Lasers in Engineering*, 2005, 43, 951-962 p. **DOI:** 10.1016/j.optlaseng.2004.10.004.

[11] M. Ragulskis, R. Maskeliūnas, L. Ragulskis. Plotting moire fringes for circular structures from FEM results. *Experimental Techniques*, 2002, 26(1), 31-35 p. **DOI:** https://doi.org/10.1111/j.1747-1567.2002.tb00054.x.

[12] K. Ragulskis, R. Maskeliūnas, L. Zubavičius. Analysis of structural vibrations using time averaged shadow moiré. *Journal of Vibroengineering*, 2006, 8(3), 26-29 p.

[13] M. Ragulskis, L. Saunorienė, J. Ragulskienė. Interpretation of fringes produced by time average reflection moire on a circular disc. *Optics and Lasers in Engineering*, 2006, 44, 1209-1218 p. **DOI:** https://doi.org/10.1016/j.optlaseng.2005.10.006.

[14] L. Saunorienė; M. Ragulskis, 2010. *Time – Averaged Moire Fringes.* Lambert Academic Publishing. P. 148.

[15] V. A. Soifer. Компьютерная обработка изображений. (Computer processing of images). *Herald of the Russian Academy of Sciences*, 2001, 71(2), 119-129 p.

[16] S. P. Timoshenko; J. N. Goodier, 1975. *Теория упругости. (Theory of Elasticity).* Moscow: Nauka. P. 576.

[17] C. Vest, 1982. *Голографическая интерферометрия. (Holographic Interferometry).* Moscow: Mir. P. 504.

Author for contacts:
Arvydas Pauliukas
Vytautas Magnus University
Studentų Str. 11, LT-53361, Akademija, Kaunas District, Lithuania
E-mail: arvydas.pauliukas@vdu.lt