JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
46, 4, pp. 845-867, Warsaw 2008

APPLICATION OF NON-CONTACT METHODS TO EXPERIMENTAL MEASUREMENTS OF HUMAN BODY VIBRATION

Marek A. Książek
Janusz Tarnowski

Cracow University of Technology, Institute of Applied Mechanics, Cracow, Poland
e-mail: ksiazek@mech.pk.edu.pl; jantarno@mech.pk.edu.pl

In the paper, the application of non-contact methods used in experimental measurements of human body vibration is discussed. The most applicable and commonly used non-contact methods of measurements are the methods based on lasers and high speed video cameras. In the paper, chosen experimental measurements of human body vibration by non-contact methods, done by the authors and described in separate articles, have been presented. The study shows how direct measurements of displacements registered marked points of the human body submitted to vibration and allowed kinematical and dynamical analysis leading to estimation of harmful exposures. The following paragraphs of the paper contain examples of experimental measurements and conclusions concerning the comparison of classical and non-contact methods including their suitability, advantages and disadvantages in the measurements of dynamical behaviour of the human body.

Key words: non-contact methods, human body, vibration measurements

1. Introduction

Progress in the knowledge of such a magnificent biomechanism as the human body forced scientists to a deeper penetration in the nature of all its vital phenomena and reactions to external excitations. It was possible only by application of the most advanced methods of measurements and registration of well defined physical quantities. All kinds of experiments and measurements with participation of human beings belong to the most difficult ones and contain the largest margin of incertitude. Some of the parameters such as temperature, body dimensions, and weight can be considered as constant; others, for example, blood pressure and pulse are slowly varying. These parameters are measured by relatively simple devices but, in general, continuous physiological changes of all live organisms require specially designed instruments of measurement.

In the paper, the methods of measurement of human body vibrations have been presented and discussed. The human body vibration is, in most cases, described by displacements, velocities and accelerations of chosen points of skin. In the biomechanical approach the measurement of forces is also indispensable. Measurements of all primordial kinematic and dynamic parameters allow description of the human body's behaviour subjected to vibration excitations and its actions and reactions with machines, hand tools and other devices.

Classical methods of measurement require fixation of transducers on the body which alter real signals by their dimensions and inertia. It is particularly objectionable and leads to false results when one wants to measure simultaneously kinematic values at several points of skin or small surfaces of the body. Application of non-contact methods do not disturb the measured places, so the values of registered signals can be considered true and fully describing the displacements of selected surfaces of the body. Measurements by non-contact methods based on information are carried by waves of light reflected from the surfaces of measured subjects. The most natural and most frequently used in practice are non-contact methods based on the application of high speed cameras with lenses reacting on visible and infrared radiation. The high speed cameras coupled with the computer software of picture analysis are particularly useful for monitoring, dynamic measurements and registration of chosen parts of the human body. Lasers are other devices frequently used for non-contact measurements such as mechanical and biomedical sensors. The lasers based on triangulation [19] and Doppler's phenomena (Halkon, 2001; 26, 29) are used correspondingly for displacement and velocity measurements. Laser application to measurements of living objects is sometimes limited because of their harmful effects on eyes and skin. The second drawback of laser application to measurements of dynamical behaviour of the human body is the difficulty with keeping an appropriate correlation between the laser ray and the measured direction (Backteman, 1998). It leads to inappropriate rebounds of laser rays. The measurement technique is continuously improved and advanced laser vibration meters (Castellini, 2006) allow scanning of chosen parts of the investigated subjects.

Technological progress in high speed cameras systems is described in Hoffberg *et al.* (1997). The principle of measurement by high speed camera relies on filming and registration of sequences of pictures of chosen parts of the body and subsequent numerical analysis of these sequences as functions of time. Presently, standard transducers of pictures allow for registration of about 10000 frames per second using full resolution. For special purposes, the velocity of registration may be extended to $2.5 \cdot 10^6$ frames per second [27]. The velocity of registration may be augmented by the controlled diminishing of picture surfaces. For tracking and registration of chosen points of an object, subpixel resolution may be applied (Frischolz, 1993; Shekarforoush, 1995). The subpixel resolution corresponds to the application of transducers with higher resolution. The tests on resolution with application of subpixel technology, done at the University of Utah (USA) and described in Welch and Van Gemert (1995), showed that the effective resolution may be equal to 0.005% of the picture surface.

The second important component of measurements by high speed cameras, apart from registration, is a system allowing for motion analysis described in Frischolz [6], Frischolz and Wittenberg [7], Ploskas *et al.* (2003). Such a system allows a sequential approach to the problem. The two steps (registration and analysis) can be done independently at different times. An exemplary software for motion analysis based on the registered pictures is described in [25].

There are some advantages and drawbacks of the non-contact methods based on high speed camera registration and motion analysis software. The major advantages can be itemized as follows: possibility of registration of motion of practically unlimited surfaces of a vibrating object, lack of material transducers attached to the investigated part of the body, possibility of registration of big relative displacements of several segments being in motion, for example, in the hand-handle-tool system. There are no cable noise connected to piezoelectric accelerometers as in the classical method, where good quality cables and connectors are required and the cable should be isolated from the vibrating surface near its connection with accelerometers so that bending movement during vibration is minimized. High speed camera non-contact methods are particularly suitable for measurements of vibration and shocks of the hand tool-hand-arm system. Several manufacturers of accelerometers used in classical approaches and some standards recommend that accelerometers should not be used for accessing excessive hand-transmitted vibration and shocks because their sensitivities are often too low. Big measurement errors may occur when the accelerometers are exposed to vibration and shocks of chisels, pneumatic chippers and other percussive tools.

The principal drawback of the presented method is related to the bands of frequency and values of amplitudes of the measured signals. Vibration with a low frequency and a big amplitude of displacement is relatively well registered and analysed. The application of a method to high frequency and small amplitude vibration measurements leads to big, direct errors. In that case, the analysis and interpretation of the obtained results should be verified and validated by application of another methods. Human body vibration is characterised by low frequencies, but most international standards, when describing the influence of vibration on the human body, use acceleration as the fundamental estimator. Calculation of acceleration from pictures registered by a high speed camera relies on double integration of the displacement signal. It generally leads to indirect numerical errors, which are difficult to estimate.

2. Examples of application of non-contact methods to experimental measurements of human vibration

In the previous Section, the principal advantages of non-contact methods based on the application of laser and high speed cameras to measurements of systems with human operators have been presented. The chosen exemplary measurements, which could not be realised by classical methods, were done at the Laboratory of Dynamics of Material Systems of Cracow University of Technology. The investigations were based on optical measurements of time varying displacements of chosen points marked on the human body. The vibration of the following parts of the human body were measured: chosen points of the hand-arm system of a human operator excited by a shaker, vibration of the head of a sitting man subjected to vertical vibration, chosen points of the vertebral column of a standing woman subjected to a vertical harmonic excitation. In all cases, the sequences of acquisitioned data were registered and subsequently analysed by a special software. The results of the analysis of displacements have also been used for further indirect estimation of such quantities as velocity, acceleration, energy distribution and force.

2.1. Investigations of the effect of pressure and excitation frequency on hand vibration measured by laser transducers

The purpose of the investigations was to measure the influence of the pushing force between the hand and tool handle on the vibration of the hand. The measurements have been done on the stand shown in Fig. 1.

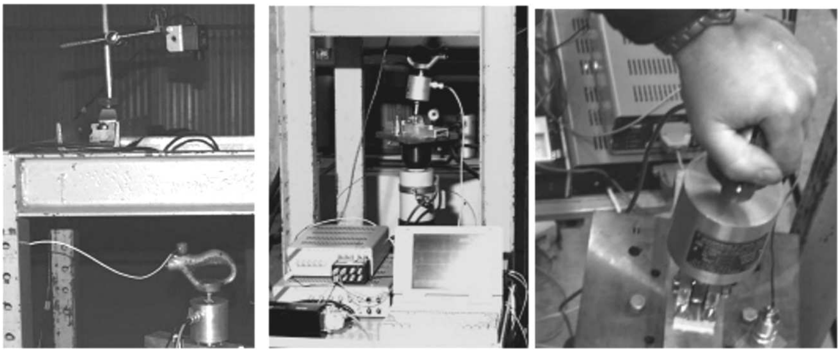

Fig. 1. Photos of the main parts of the measurement stand: handle, shaker, force meter and the hand with a marked point

The application of the non-contact method allowed measurement of vibration directly on the hand of the human operator and investigation of the influence of the pushing force P on the transmissibility of the force as a function of frequency. The measurement of displacements of chosen points of the operator's hand were made by two laser transducers whose rays were focused on two points of the operator's hand: on the middle finger's carpal bone and on the metacarpal part of the hand. The electro-hydraulic shaker was used as the source of vibration. The vibration was transmitted from the shaker through the force transducer to a specially prepared handle. The handle was pushed by a fixed and monitored force. Three different values of the pushing force, established and constant for each series of measurements were measured by a strain gauge transducer and monitored by a needle indicator for all frequencies of the excitation in the range 20-100 Hz. Numerical analysis of the registered signals supplied the information about the displacement amplitude and the phase of signals for each of the applied frequency and marked point on the hand and handle. Exemplary relations between the amplitudes are shown in Fig. 2. More results of this kind of experimental investigation can be found in Książek and Tarnowski (2001). Similar experiments were done in Deboli *et al.* (1999) with a laser vibrometer based on Doppler's phenomena. The application of classical accelerometers according to the instructions described in PN-91/N-01353 or ISO 5349 Standards allows estimation of the level of exposure at a chosen point of the system, but the lack of co-linearity between the accelerometers attached to the handle and hand excludes precise establishment of transmissibility functions between the considered points.

As shown in Fig. 2, the displacements on parts of the hand are bigger than those on the handle. It means that the hand-arm system in the presented configuration acts as an actuator of vibration.

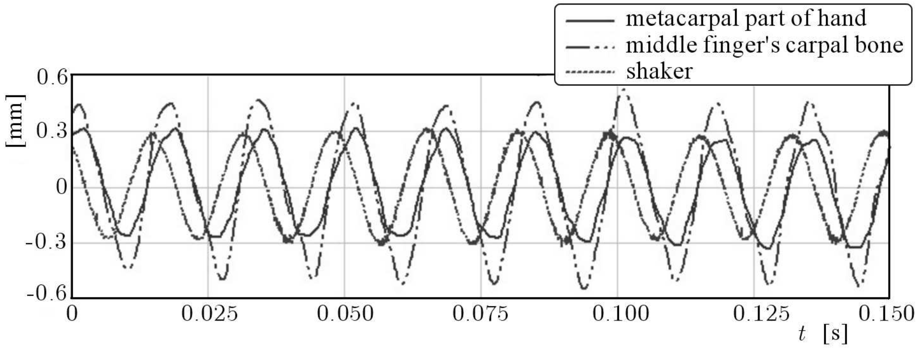

Fig. 2. Time history of the displacements of points of the hand and handle for frequency excitation 50 Hz

2.2. Identification of displacement and acceleration transmissibilities of the tool-hand-arm system

The results of investigations presented in this Section have been obtained from three series of measurements carried out by classical and non-contact methods. The classical method is based on miniature accelerometers glued to the handle and hand. The non-contact method is based on a high speed video camera and the application of motion analysis software. The measurements had two principal targets:

1) the estimation of magnitude and phase of the displacement and acceleration transmissibilities between the handle and several chosen points of the hand,
2) comparison of the results obtained by each method.

The source of excitation was, as previously, the electro-hydraulic shaker controlled by a sinusoidal signal with a sampled frequency within the range 20-130 Hz. The measurement stand used in the experiment is shown in Fig. 3. Two series of measurements were done by the camera and one by the accelerometers. The measurements were made by the system allowing registration and analysis of 350 full pictures per second. Simultaneously, two miniature accelerometers were mounted. The registered signals were analysed with special motion analysis software, compared, and graphically illustrated.

In Figs. 4 and 5, exemplary frames with marked points on the hand and handles, and the corresponding time histories of displacements of these points for the harmonic excitation with two frequencies 52 and 25 Hz are shown.

Analysing the presented time histories of acceleration, one notices the significant influence of the frequency excitation on the value of transferred vibration

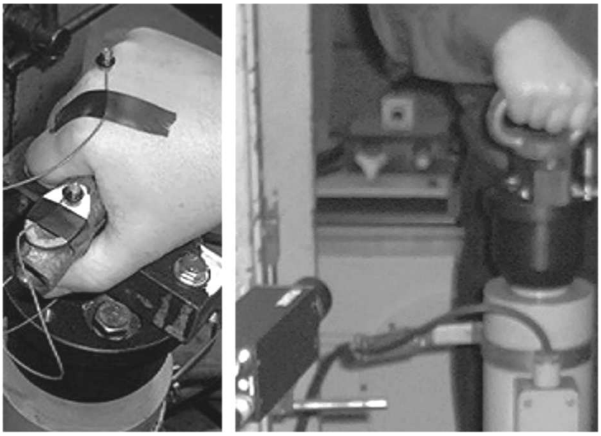

Fig. 3. Measurement stands with accelerometers and a high speed video camera

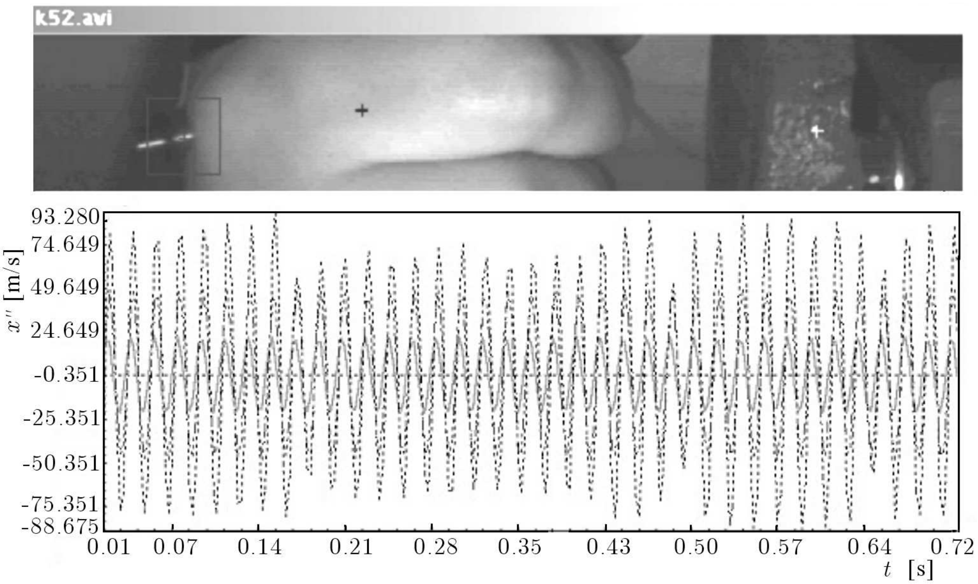

Fig. 4. A chosen frame of the registered picture and corresponding time histories for frequency excitation $f = 52\,\mathrm{Hz}$

towards different points of the hand. The data acquired from the experiments and the application of the Matlab environment allowed for calculation of the magnitude and phase of the acceleration transmissibility between the handle and chosen points of the hand for three considered series of measurements. The final results are shown in Fig. 6.

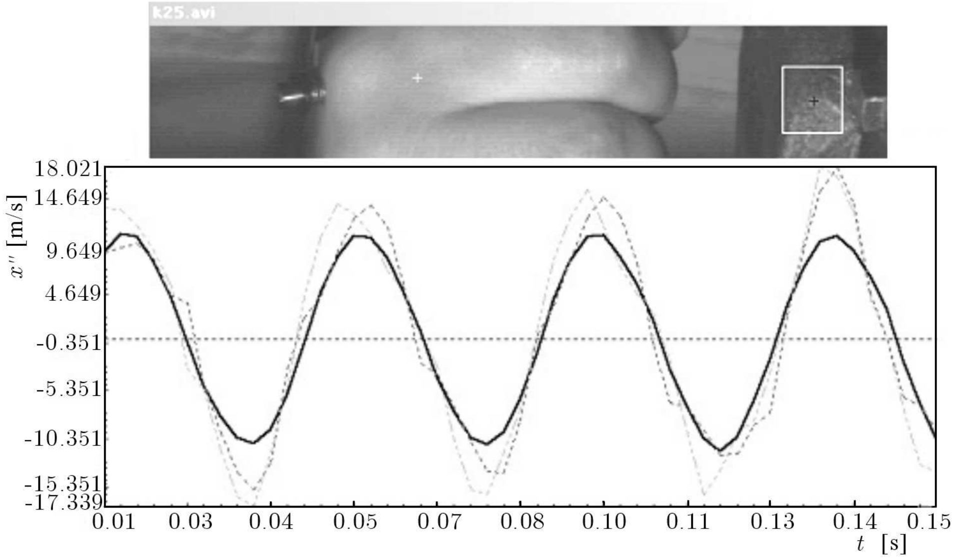

Fig. 5. A chosen frame of the registered picture and corresponding time histories for excitation $f = 25\,\text{Hz}$

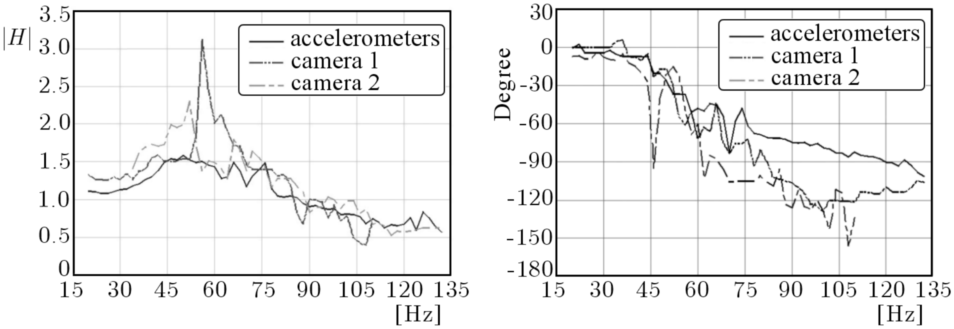

Fig. 6. Magnitudes and phases of the transmissibility function for three series of measurements

Inspection of the diagrams shows big differences between the results obtained by the classical and non-contact method. One can notice that even very light accelerometer changes, particularly within the band of resonance frequencies, have big influence on the value of the transmitted amplitude. The complete description of the investigations together with the discussion of the obtained results was presented in Książek and Tarnowski (2002b).

2.3. Estimation of the transmissibility function between the seat and operator's head

The estimation of magnitude and phase of the transmissibility function between the seat and the operator's head by the use of a high speed camera-motion analyser system was the target of the experiment presented in this Section. Because of the big distance between the seat and the operator's head, some adaptations of the experiment technique were introduced. It allowed for simultaneous measurements of the seat and the sitting body.

A specially designed operator's seat was fixed to a shaker platform. Ten volunteers were submitted to harmonic vertical vibration with a frequency changing sequentially within the range 0.5-20 Hz. The shaker was driven by the signal coming from a sine generator. Difficulties with the measurement of phases forced a higher resolution of the camera and caused a small scale of the taken picture.

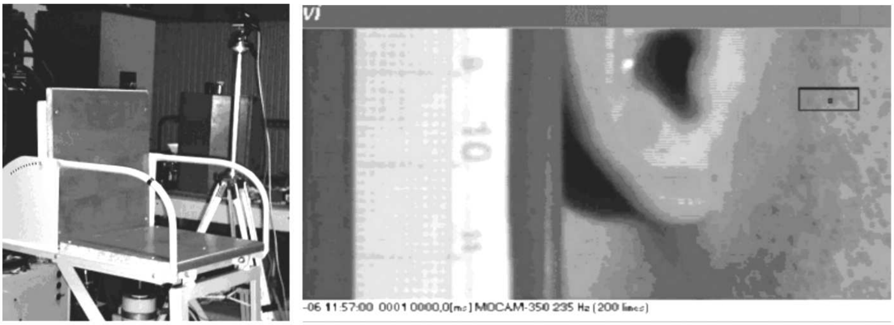

Fig. 7. The measurement stand with the seat (left). An examplary frame of the picture (right)

Figure 7 shows the seat fixed to the shaker and an examplary frame of the picture. At the left part of the frame a piece of a steel beam was placed with a milimiter scale fixed to the seat. It allowed simultaneous registration of the head and seat vibration. The magnitudes and phase of transmissibility of velocities of marked points calculated on the base of registered results are shown in Fig. 8.

In Książek (1999) and Książek *et al.* (2004) it was shown that in the case of a sitting human body the results obtained by the non-contact and classical methods are similar.

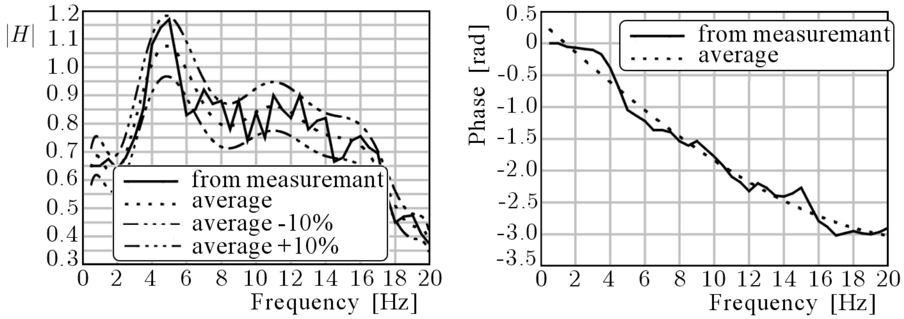

Fig. 8. Magnitude and phase of the velocity transmissibility

2.4. Experimental measurements of nonstationary processes of the arm-hand-tool handle system

In this Section, results of experimental measurements of nonstationary processes of the arm-hand-tool handle system are presented. The measurements were done on a laboratory stand by application of a high-speed video camera and a software for the computer analysis of motion (Książek and Tarnowski, 2003). Direct measurement on the hand's knuckle allowed estimation of the adaptation time of the hand to such components as the frequency excitation and pressure of the hand on the handle. Transient states are very common during work with hand held tools. Work with such tools is very often interrupted. The analysis of transient, nonstationary states is then very important if one wants to define the short adaptation time of the operator's hand to changing conditions of the excitation. The time of adaptation depends on some operational parameters. After being switched on, the hand-held tool needs some transient time to achieve its steady state regime of functioning. We can assume that in this time the operator's hand follows, and in an optimal way, adapts to changing excitation conditions. The analysis of vibration on chosen knuckles of the operator's hand become possible thanks to the application of a high-speed video camera and the application of a suitable software for motion data acquisition. The following stages of experiments were done:

1) stand measurements for sinusoidal excitations with frequencies 10, 20, 30, 40, 50, 60,70 and 80 Hz – transient processes of the vibration increase on the handle and operator's hand were registered from switching on the shaker up to the state considered as steady,
2) measurements on a heavy electrical percussive drill, where transient vibrations of the tool and hand were registered from switching on up to the steady state,

3) stand measurements with sinusoidal excitations, where the hand and handle vibrations were registered during frequency and amplitude variations of the shaker,
4) stand measurements of the drill's handle for sinusoidal excitations composed of the main frequencies obtained from spectral analysis of drill vibrations.

The transient vibrations of the hand and handle were registered from switching on and off moments up to the corresponding steady states of the system. The measurement stand was built on an electro-hydraulic shaker. A typical hand-held tool's handle held by a standing operator was fixed to the adapted vibrating shaker's head. The shaker was controlled by sinusoidal functions of the displacement with the frequencies mentioned above. Heavy percussive drilling in the cement block was kept in one hand and slightly pushed down by the operator. The motion of the drill was registered by the camera recording 350 full frames of the moving picture per second. The measurement stand with the shaker is shown in Fig. 1. Several series of measurements for two operators were done. Each series was carried out for the two following states (two values of the pressure force applied to the handle by the operator):

1) the handle of the tool was only kept without pressure,
2) the handle of the tool was kept and pressed by the operator with the constant force 80 N.

The registered pictures, in form of bitmap sequences were introduced into computer memory. The object's motion registered on the films was subsequently analysed by the specialised software. Using this software, one can track and analyse motion of each pixel of the picture with the 1/3 subpixel accuracy. In Fig. 9, the time history of transient amplitudes of displacements on the hand and handle are presented for the excitation frequency 40 Hz and the pressure force equal to 0 N and 80 N. The time histories of amplitudes of the relative displacements between the chosen points of the hand and handle for the assumed frequencies and force pressure are presented in Fig. 10.

Big influence of the excitation frequency and pressure force on the increase of amplitudes of the system during the starting period of tool's work is very clearly noticeable.

As the final remark, it should be emphasized that the acquisition of all the presented results in this Section would be impossible to be realised by the classical method.

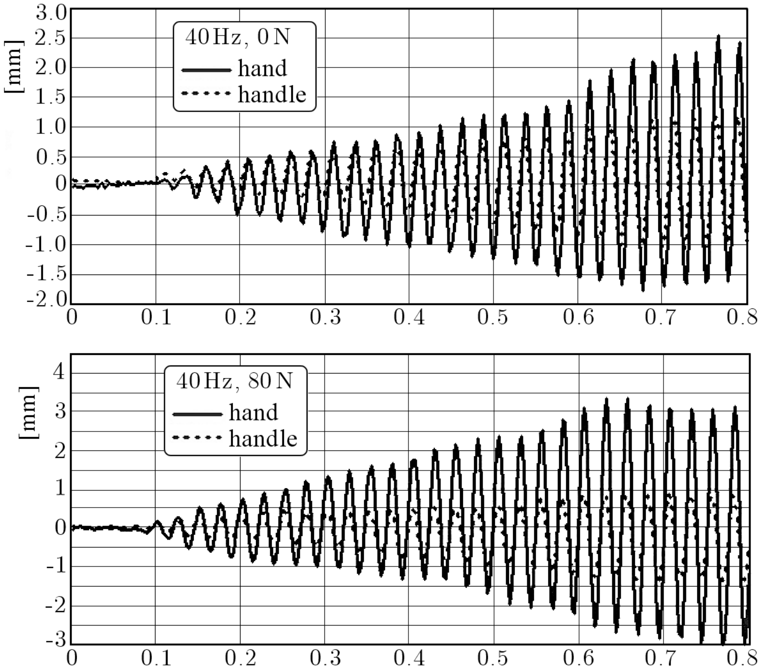

Fig. 9. Exemplary displacements of two chosen points on the hand and handle in the time domain for a sinusoidal excitation with the frequency 40 Hz and force pressure 80 N

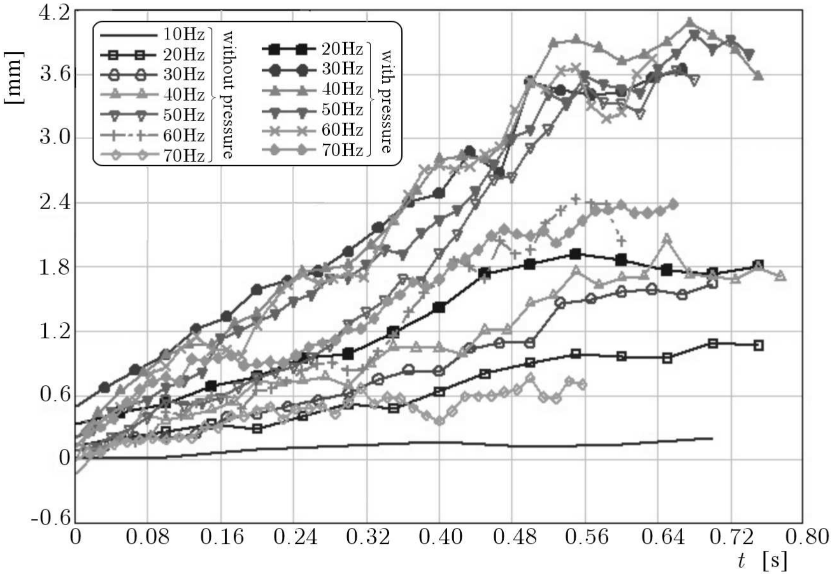

Fig. 10. Transient relative amplitudes of displacements of chosen points on the hand and handle

2.5. High-speed camera experimental investigations of the power absorbed in the hand-arm-tool's handle system

One of the most important components in experimental investigations of the absorbed power by dynamic systems is the phase shift between the measured force and velocity. In the presented investigations, a new method of estimation of the phase angle shift between the force and velocity transmitted to the system is proposed. This method allows for limitation of errors due to different kinds of force transducers and kinematic parameters in measurement applications.

Work with hand-held tools may be a cause of pain due to vibration exposure. There are two principal approaches to summarizing knowledge concerning this subject. The first of them is the assessment of the vibration dose transmitted to the human body by application of the weighting acceleration method (Burstrom *et al.*, 1998), presented in ISO 5349 standard. The second approach is based upon the measurement assessing the absorbed power by the operator's hand-arm system. The application of the second approach in laboratory conditions was presented in Lenzuni and Lundstrom (2000). In general, the power absorbed by a dynamic system is the real part of the scalar product of the force $\boldsymbol{F}$ and velocity $\boldsymbol{V}$ vectors

$$P_{Re} = \boldsymbol{V}\boldsymbol{F} = VF\cos\varphi \tag{2.1}$$

where φ is the phase angle between $\boldsymbol{F}$ and $\boldsymbol{V}$. The phase angle is then one of the three quantities in formula (2.1). In practice, the measurement of frequency and amplitude of the force and velocity is not difficult. Some difficulties arise in the measurement of the phase angle which depends on properties of applied transducers, amplifiers, connectors and other components of the experimental stand. In the presented investigations, the simultaneous way of force and velocity measurement is applied. It allows for good assessment of the phase angle shift and calculation of the absorbed power versus frequency in the considered band.

In the presented experiments, the method based on the high-speed camera registration and computer analysis of pictures has been applied once again. The measurement of the force and velocity was based upon the registration of relative displacements of a mechanical load indication bridle transducer.

Knowing elastic characteristics of the load indication bridle and having registered relative displacements of its upper and lower parts, it was possible to calculate the transmitted force without any additional devices or signal analysis. Such an approach guarantees that the error of measurement of real values of the signal phase is minimal. The correctness of the amplitude measurement was verified by comparison of the results obtained from the high-speed camera with the results registered by the strain gages fixed to the load indication bridle. The presented procedure of the measurement of relative displacements became possible thanks to the application of the subpixel accuracy described in Frischolz and Spinnler (1993), Shekarforoush *et al.* (1995). For example, in measurement techniques [28], instead of strain gauges it is possible to analyse the optimally searched relative displacement of two markers of a chosen edge of the moving subject in the picture. The correctness obtained in this way is about 10^{-6} m. In the mentioned paper, the displacements of the hand-handle system were measured in two steps.

Fig. 11. The measured object and an exemplary frame with considered and analysed points

The first step was registration of the displacements of all points of the considered system by the high-speed video camera. The second step was numerical calculation of kinematic values of the chosen points of registered pictures. In Fig. 11, the measured object and an exemplary frame with marked points are shown. The calculations were done by Książek and Tarnowski (2004) using the Matlab toolbox. The input data of displacements and forces obtained from the measurements were used in calculation of the absorbed energy instead of the absorbed power, to avoid numerical errors caused by signal differentiation. The mean value of the absorbed power was obtained by division of the mean work by the vibration period. The mean work can be considered as a surface of the field lying within a closed contour in the phase plane described correspondingly by the axes of force and displacements. Exemplary plots of such force and displacement contours for frequency 38 Hz are shown in Fig. 12.

To verify and compare the results of series of measurements of the absorbed power, an unloaded handle was used for sinusoidal excitations with the frequency range 50-70 Hz. This approach allowed for the assessment of lost energy in the strain gage-handle structure and calculation of the ratio betwe-

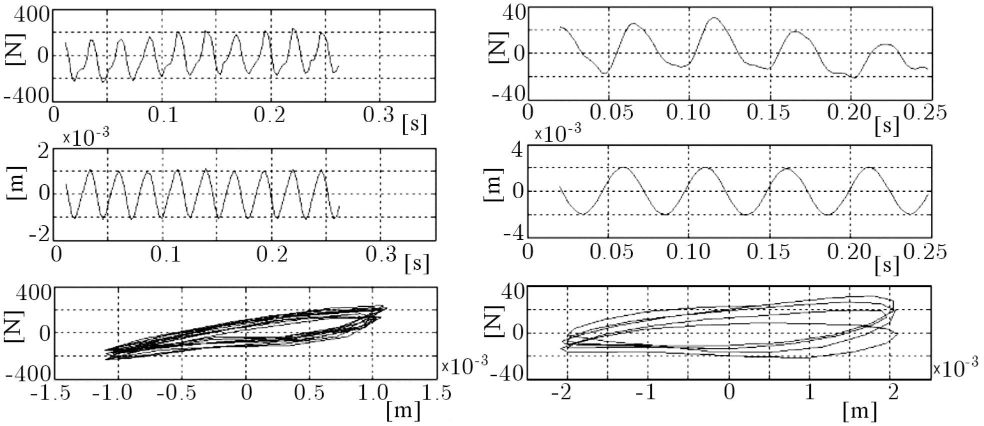

Fig. 12. Plots of force, displacement and mean work contours corresponding to sinusoidal excitation with the frequency 38 Hz (left) and 20 Hz (right)

en this energy and the total energy supplied to the hand-handle system. The absorbed power calculated for all analysed frequencies are presented in Fig. 13.

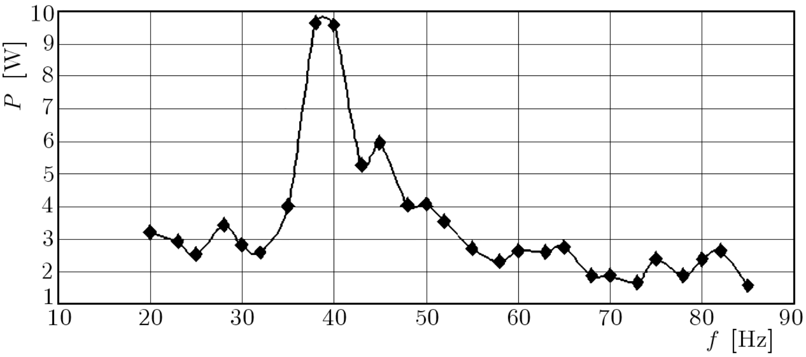

Fig. 13. Sequence of values of the absorbed power as a function of frequency

2.6. Experiments on density energy estimation in the hand-arm-hammer drill system

The measurements have been realised for two kinds of excitation sources, i.e. a real heavy drill and a hydraulic shaker described in the preceding Section. Several chosen positions of the hand arm system were measured. Application of the high-speed camera method to measurements of human body vibration allowed also for registration of motion of the whole considered part of the investigated man-machine system and subsequent numerical analysis of displacements, velocities and accelerations of its chosen points. From the registered time histories of the displacements of the chosen points, we can obtain a sort of map containing information about the distribution of energy on the whole part of the investigated object as a function of hand position and frequency excitation. The frequency of harmonic excitation of the shaker had sequentially the same frequency as the fundamental frequencies of the drill. Those frequencies were obtained by spectral analysis of the vibration emitted by the drill. In Fig. 14, two frames with marked points on the hand, whose motion was registered in two mutually perpendicular planes, are shown.

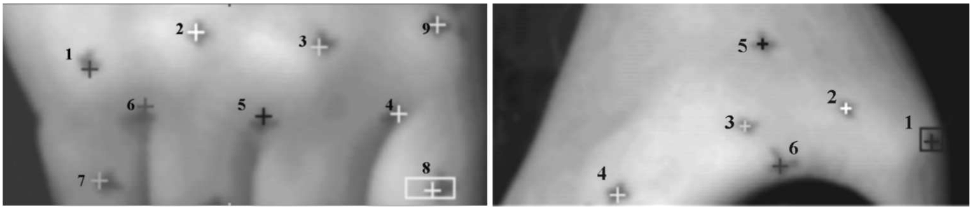

Fig. 14. Frames of two perpendicular planes showing distribution of analysed points

In both cases, the registration was done for steady state vibration. The displacements of marked points were tracked through the entire sequence of registered frames of the picture. The velocities of corresponding points were calculated by numerical differentiation and saved in computer memory. Assuming a homogenous distribution of the mass, the distribution of the kinetic energy of particular points of the hand and drill can be estimated by taking into account the quadratic values of calculated velocities as shown in Fig. 15. The quadratic values of velocities were calculated as the sum of quadratic values of their horizontal and vertical components. The number of marked points in two planes in Fig. 14 corresponds to the quadratic values in Fig. 15.

In Fig. 16, the two positions, straightened and bent, of the analysed tool handle-hand-forearm-upper arm-shoulder system are presented. All points at which the displacements were measured and their corresponding velocities calculated, are numbered from 1 to 7. Point number 8 corresponds to the point on the tool handle. The measurements were done for the straightened and bent hand-arm system and excitation frequencies equal to 11, 37, 49 and 59 Hz, and presented in Książek and Tarnowski (2002a). Exemplary results for 11 Hz are shown in Fig. 16.

It has been shown that the energy of different points of the hand depends on their position and position of the hand-arm system. The results are impossible to be obtained by classical methods.

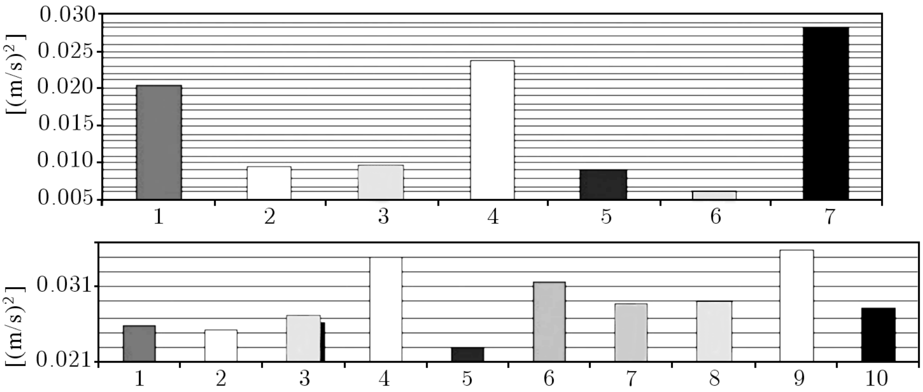

Fig. 15. Mean values of quadratic values of velocities of points chosen on the hand

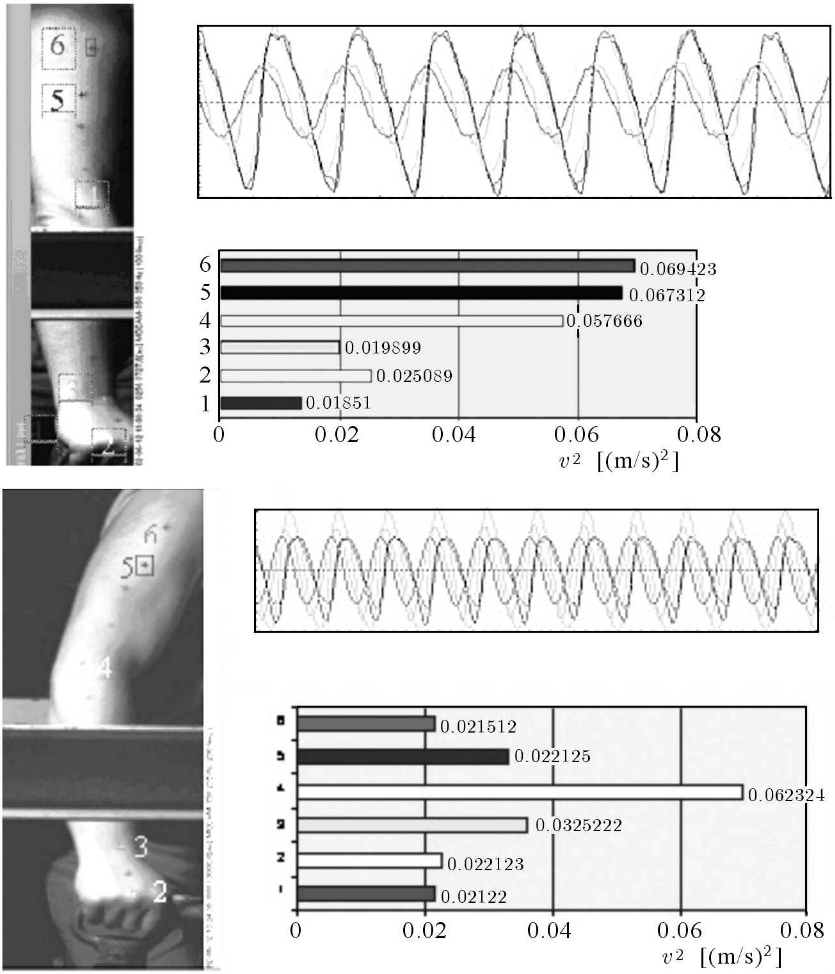

Fig. 16. Straightened and bent hand and quadratic values of velocities, for the frequency excitation 11 Hz

2.7. Examplary experimental investigations of the effect of low-frequency training on vibration of selected backbone sections

The study presents experimental data of selected human vertebra sections in the course of day-by-day training sections. The control group included female volunteers subjected to low-frequency vibration exposure. The experiments were conducted using a high speed camera and computer image processing techniques.

The experiments were carried out during low-frequency training sessions. The control group included 28 female volunteers from various age groups and having different constitution of body. For subsequent 19 working days (no Saturdays and Sundays) the volunteers were subjected to 20 minutes of exposure to low-frequency vibration. During the experiments, they remained in a stand-up position. A high speed camera was used and computer-assisted techniques of motion analysis were applied in this part of experiments.

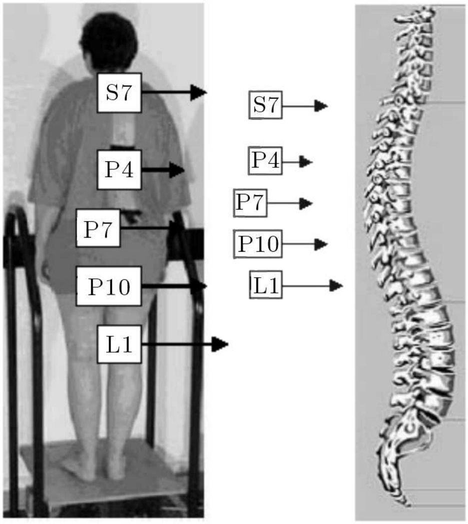

Fig. 17. (a) Examined volunteer. (b) Location of control points on the volunteer's back

Two participants were tested at the same time. Before ascending the platform, control points were selected and marked by a physician on the selected vertebrae (the same vertebrae sections for all 28 participants). Figures 17a,b show correspondingly the tested object, applied vibrating platform and the location of control points on the volunteer's back. Vibration was generated by a vibrating platform with a base-excited shaker driven by an electric motor. Harmonic vibration of the frequency 3.2 Hz (near the frequency of a running man) and the same amplitude were applied through the whole experimental program. Motion of each chosen point of the tested objects was registered by the high speed camera at the rate of 350 frames per second and stored in the memory of an image recorder.

Exemplary frames of the registered picture are shown in Fig. 18. In general, the computer analysis of the registered data showed the advantageous influence of low-frequency training on the selected vertebrae, which was expressed by reduction of their amplitudes. Full statistical analysis and discussion of the registered data during the experiment can be found in Tarnowski *et al.* (2006).

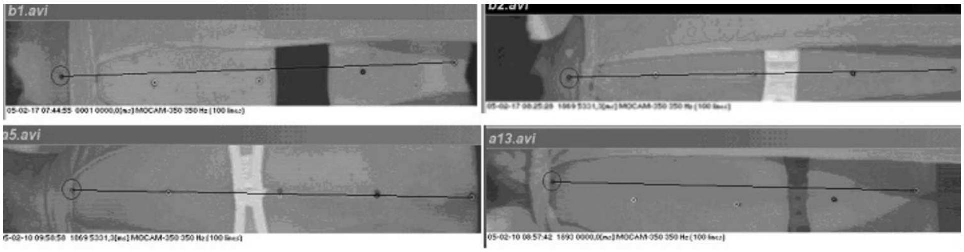

Fig. 18. Exemplary frames of registered pictures

3. Concluding remarks

To summarize the presented experiments, the following conclusions concerning non-contact methods applied to measurements of systems with a human operator presented can be enumerated as follows:

- A high speed camera allows for simultaneous registration of all parts of a measured system. The sufficient condition for propriety of the registered picture is keeping the contour of the measured object in the frame.
- A high speed camera is particularly effective in measurements of low-frequency vibration.
- A registered picture by a high speed camera allows estimation of two mutually perpendicular components of the displacement vector and, after differentiation, values of velocities and accelerations of considered points. It can be easily used for comparison with a basicentric co-ordinate system directions of the human body, shown in the standards.
- High speed camera measurements allow for estimation of the direction vibration propagation as a function of time and position of the body.

- Presently, by the use of subpixel resolution and the newest lenses one, can measure vibration displacements with amplitudes of the order of 10^{-6} m.
- A human body subjected to vibration is a very difficult object for measurements by laser vibrometers and scanners. A typical measurement with laser is limited to a chosen direction of the laser ray. Continuously changing the position of the object practically excludes recurrence of measurements. Scanning by aser does not register the same situation because of certain time delays. It is difficult to keep a laser ray at the chosen point of the hand or another part of the human body during measurements.
- The human skin surface reflects laser rays well and has a suitable structure allowing tracking of chosen points without markers in the case of using a high speed camera and laser.
- High-frequency vibration should be measured by a laser vibrometer based on Doppler's phenomena.
- Almost all presented experiments showed that amplitudes of hands are higher than amplitudes of handles subjected to vibration. It means that the hand-arm system acts as an actuator of vibration.
- Non-contact methods allow measurement of cases of human vibration which cannot be realised by classical methods.

References

1. Backteman O., 1998, Aspects on hand arm vibration, *8th International Conference on Hand-Arm Vibration*, Umea Sweden
2. Burstrom L., Lundstrom R., Hagberg M., Nilsson T., 1998, Comparison of different measures for hand-arm vibration exposure, *Safety Science*, **28**, 1, 3-14
3. Castellini P., Martarelli M., Tommasini E.P., 2006, Laser Doppler vibrometry: development of advanced solutions answering to technology's needs, *Mechanical Systems and Signal Processing*, 1265-1285
4. Deboli R., Paone N., Rossi G.L., 1999, Comparison of laser vibrometers and accelerations to measure hand arm transmitted vibration, *Proceedings of 34th United Kingdom Group Meeting on Human Response to Vibration*, Dunton, Essex

5. Frischolz R.W., Spinnler K.P., 1993, Class of algorithms for realtime subpixel registration, *Europto Series Proceedings*, **1989**, Munchen

6. Frischolz R., Software zur automatischen Bewegungsanalyse, www.winanalyze.com

7. Frischolz R., Wittenberg T., *Computer Aided Visual Motion Analysis*, www.winanalyze.com

8. Halkon B., 2001, *The History of Laser Vibrometry and overwiew of advances in the interpretation of Non-Contact Vibration Measurements, and the Effects of Speckle Induced Noise and Inherent Motion Cross Sensivities on the Validity of a Particular Vibration Component Measurement*, Loughborough University The Department of Mechanical Engeneering, UK

9. Helmers H., Schellenberg M., 2003, CMOS vs. CCD sensors in speckle interferometry, *Optics and Laser Technology*, **35**, Elsevier Science Ltd.

10. Hoffberg M., Laird R., Lenkzsus F., Liu C., Rodricks B., Gelbart A., 1997, The development of high speed 100 fps CCD camera, *Nuclear Instruments and Methods in Physics Research*, **A 392**, 214-219

11. Książek M.A., 1999, *Modelowanie i optymalizacja układu człowiek-wibroizolator-maszyna*, Monografia nr 244, Wyd. Politechnika Krakowska

12. Książek M.A., Tarnowski J., 2001, Influence of hand pushing on handle on displacements and accelerations of operator's hand measured by non-contact method, *36th UK Group Conference on Human Response to Vibration*, Centre for Human Sciences, QinetiQ, Farnborough UK, 333-344

13. Książek M.A., Tarnowski J., 2002a, Experiments on density energy estimation in a hand-hammer drill system, *13th Conference of European Society of Biomechanics*, Wrocław, Poland

14. Książek M.A., Tarnowski J., 2002b, Measurements and modelling of hand-handle system, *37th United Kingdom Conference on Human Responses to Vibration*, Department of Human Sciences, Loughborough University, UK

15. Książek M.A., Tarnowski J., 2003, Measurements of transient vibrations of arm-hand-tool's handle system, *38th United Kingdom Conference on Human Response to Vibration*, Institute of Naval Medicine, Alverstoke, Gosport, PO12 2DL, England

16. Książek M.A., Tarnowski J., 2004, High speed camera investigations of power absorbed by hand-arm-tool's handle system, *Structures-Waves-Human Hhealth*, **XIII**, 2: *Waves-Human-Biomedical Engineering*, 143-152, Kraków

17. Książek M.A., Tarnowski J., Janik A., 2004, Badania doświadczalne wibracji siedzącego człowieka z użyciem szybkiej kamery wideo, *Czasopismo Techniczne*, **5-M**, 175-182

18. Lenzuni P., Lundstrom R., 2000, Guidelines for conducting laboratory measurements of the power absorbed by the hand and arm, *Appendix H3D to Final Report May 2001 EC Biomed II concerted action BMH4-CT98-3291*

19. *OptoNCDT 1605 Non-Contact Optical Displacement Measuring System Instruction Manual*, Esa Messtechnik GmbH Munchen, Micro-Epsilon Messtechnik Orfenburg

20. Ploskas N., Simitopoulos D., Tzovaras D., Triantafyllidis G.A., Strintzis M.G., 2003, Rigid and non-rigid 3D motion estimation from multiview image sequences, *Signal Processing, Image Communication*, **18**, 185-202, Elsevier Science

21. Shekarforoush H., Berthod M., Zerubia J., 1995, Subpixel image registration by estimating the polyphase decomposition of the cross power spectrum, *INRIA*, **2707**

22. Tarnowski J., Książek M.A., Damijan Z., 2006, Experimental investigations of the effects of low frequency training on vibration of selected backbone sections, *Molecular and Quantum Acoustics Annual Journal*, **27**, Gliwice, 285-294

23. Welch S.S., 1993, Effects of window size and shape on accuracy of subpixel centroid estimation of target images, *NASA Technical Paper*, **3331**

24. Welch A.J., Van Gemert M.J.C., 1995, Optical-thermal response of laser irradiated tissue, *Lasers, Photonics and Electro-Optics*

25. *WINanalyze. Automatic Motion Analysis. Manual, Mikromak Mikroelektronik fur Messtechnik*, Anlagen und Kamerasysteme GmbH

26. www.bksv.com

27. www.cordin.com

28. www.limess.com

29. www.polytec.com

30. www.rit.edu/ andpph/text-hs-history.html

Zastosowanie metod bezkontaktowych do badania drgań ciała ludzkiego

Sreszczenie

W pracy przedstawiono zstosowanie metod bezkontaktowych do badania drgań ciała ludzkiego. Najczęściej stosowanymi metodami bezkontaktowymi do tego typu badań są metody oparte na wykorzystaniu laserów i szybkich kamer wideo. W niniejszej pracy zostały zaprezentowane wybrane pomiary eksperymentalne ciała człowieka poddanego wibracjom, wykonane i opisane przez autorów w oddzielnych artykułach. Pokazano, jak bezpośrednie pomiary przemieszczeń wybranych punktów ciała człowieka poddanego wibracjom umożliwiają kinematyczną i dynamiczną analizę prowadzącą w konsekwencji do oszacowania zagrożeń pochodzących od wibracji miejscowej i ogólnej. W kolejnych punktach prezentowanego artykułu przedstawiono charakterystyczne przykłady pomiarów wibracji miejscowej i ogólnej ciała człowieka za pomocą metod bezkontaktowych, porównano uzyskane wyniki z wynikami otrzymanymi za pomocą metod klasycznych oraz przedstawiono zalety i wady prezentowanych metod.

Manuscript received March 31, 2008; accepted for print May 19, 2008