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# FREQUENCY RESPONSE OF CRANE OPERATOR'S SPINAL COLUMN TO RANDOM VIBRATIONS

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**Abstract**. *Regarding impact of vibrations upon health, working activities and comfort of working machines operator, research of vibrations in different working regimes of bridge crane is done. Based on the results of vibration investigations the vibration influence upon human health, working activities and comfort in accordance with international standard ISO 2631-1 is analyzed. For working regimes, which were potentially critical according to this analysis, an analysis of dynamic behavior of operator's spinal column is done. As a result of the modal analysis natural frequencies and vibration mode shapes of spinal column within frequency range of working vibrations are determined; also, as a result of the conducted time-history analysis, the load of each vertebrae is determined. Human body is modeled by means of finite elements, so spinal column, visceral column, head, torso segments, pelvis and buttocks tissue are modeled in the midd-sagital plane by means of elements such as: beam, spring and mass element.*

## 1. INTRODUCTION

Daily exposure of the mobile working machine operator to the influence of whole-body vibrations may cause health problems; it also affects his working activities and comfort. Thereby, the influence of whole-body vibrations is an object of international standard ISO 2631-1 [1], which classifies influence of this type of vibrations to health, working activities and comfort.

That is why the research of bridge crane vibrations in different working regimes was conducted, in order to find out its influence on the crane operator. Based on the experimentally obtained results there was, according to standard ISO 2631-1, an analysis done of influence of bridge crane vibrations on health, working activities and comfort of crane operator. For those working regimes, which seemed to be potentially critical according to this analysis, there was conducted a modal analysis by which natural frequencies and vi-

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bration mode shapes of spinal column were determined; there was also a time-history analysis by which loads of each vertebrae, caused by vibrations, were determined.

Recently, a number of biomechanical models has been suggested for analysis of dynamic behavior of human spinal column, which were based on finite elements (Belytschko et al., 1985, [3]; Kitazaki, 1994, [4]; Pankoke et al., 1998 and 2001, [5,6]). The modal and time-history analyses presented in this paper are conducted according to model of Kitazaki. The mentioned analyses were realized with commercial software for finite element analysis ANSYS-PC/Linear 5.3 (Swanson Analysis System, Inc.).

## 2. METHODS

### Object of vibrational research

Research of vertical vibrations was conducted in factory MIN, Nis, on the bridge crane shown in Fig. 1. Span of bridge crane girders is L = 30 m, and maximal load capacity is F = 50 kN. Long span and elasticity of bridge crane girders cause severe vibrations during the crane's operation.

Fig. 1. Bridge crane on which research was conducted

### Vibration analysis according to standard ISO 2631-1

Third-octave band analysis of acceleration spectra is applied for evaluation of vibration influence on human body according to standard ISO 2631-1. According to third-octave band analysis, frequency range of vibration spectrum, that human body is exposed to, is divided into subranges of width equal to one-third octave with mean frequencies in accordance with standard ISO 266 [2]. For such frequency bands of one-third octave width effective acceleration could be determined by the following equation:

$$a_i = \left[ \frac{1}{\tau_i} \cdot \int_0^{\tau_i} a_i^2(t) \cdot dt \right]^{\frac{1}{2}}, \qquad i = \overline{1, n} \tag{1}$$

where $a_i$ is effective acceleration of i-th one-third octave frequency band, $a_i(t)$ measured acceleration of vibrations within i-th one-third octave frequency band, $\tau_i$ time of duration of vibrations within i-th one-third octave frequency band and n number of one-third octave frequency bands.

After determination of effective acceleration of one-third octave frequency bands, crest factor of measured vibration spectrum could be determined by the following equation:

$$f_c = \frac{a_{max}}{a_{i,max}} \tag{2}$$

where $f_c$ is crest factor, $a_{max}$ maximal instantaneous acceleration peak value of measured vibrations, $a_{i,max}$ effective acceleration of one-third octave band containing value of maximal instantaneous acceleration peak. Evaluation of vibration influence on working comfort of crane operator in case that crest factor is not greater than 9, according to ISO 2631-1, is based on overall effective acceleration of vibration spectrum.

Overall effective acceleration value of measured vibration spectrum is determined on basis of effective acceleration of one-third octave frequency bands. Regarding different influence of vibrations within different one-third octave bands on human body, overall effective acceleration is determined by weighting effective acceleration of one-third octave bands, in a way proposed by standard ISO 2631-1:

$$a_w = \left[ \sum_{i=1}^{n} (w_i \cdot a_{w,i})^2 \right]^{\frac{1}{2}} \tag{3}$$

where $a_w$ is overall effective acceleration of measured vibration spectrum, $w_i$ weight factor of i-th one-third octave frequecy band proposed by standard ISO 2631-1.

## MODAL ANALYSIS

When the equations of motion for dynamic model are constructed, the modal analysis is conducted to determine the natural frequencies and the vibration mode shapes. The equation of motion for free vibrations of an undamped system can be written in matrix form in the following way [10]:

$$[M] \cdot \{\ddot{q}(t)\} + [K] \cdot \{q(t)\} = 0 \tag{4}$$

where [M] is mass matrix, [K] stiffness matrix, $\{\ddot{q}(t)\}$ acceleration vector, q(t) displacement vector and t time. For harmonic motion, displacement can be assumed in the following form:

$$\{q(t)\} = \{u\} \cdot \sin(\omega \cdot t) \tag{5}$$

Substituting equation (5) into (4) it is obtained:

$$[K - \omega^2 \cdot M] \cdot \{u\} = 0 \tag{6}$$

Previous equation describes a classical eigenvalue problem. The eigenvalues $\omega_1^2$, $\omega_2^2$,... $\omega_N^2$ can be obtained if the determinant of the matrix in equation (6) is equal zero:

$$\det[K - \omega^2 \cdot M] = 0 \tag{7}$$

The quantities $\omega_1^2$, $\omega_2^2$,... $\omega_N^2$ correspond to natural frequencies, and substituting each of obtained eigenvalues into equation (6), associated eigenvectors $\{u_1\}$, $\{u_2\}$,..$\{u_N\}$ are obtained. The eigenvectors $\{u_1\}$, $\{u_2\}$,..$\{u_N\}$ correspond to the vibration mode shapes.

### Time-history analysis

Time-history analysis is used for determinantion of displacements, strains, stresses and forces of dynamic model acted upon by alternate excitation forces. One of methods for time-history analysis is mode-superposition method, which has to be preceded by modal analysis. In case of using this method, starting point are equations of motion, which are in matrix form expressed in the following way [10]:

$$[M] \cdot \{\ddot{q}(t)\} + [K] \cdot \{q(t)\} = \{F\} \cdot e^{i \cdot \Omega \cdot t} \tag{8}$$

where $\{F\}$ is vector of forces acting in model nodes, $\Omega$ angular excitation frequency.

The effect of vibration damping of dynamic model is included after mode-superposition method through the use of effective damping ratio so called modal viscous damping at each vibration mode shape.

When using the following substitution:

$$\{q(t)\} = [\Psi] \cdot \{y(t)\} \tag{9}$$

and taking into account damping, equation (8) can be expressed in the following form:

$$\{\ddot{y}(t)\} + [C] \cdot \{\dot{y}(t)\} + [\omega_j^2] \cdot \{y(t)\} = [\Psi]^T \cdot \{F\} \cdot e^{i \cdot \Omega \cdot t} \tag{10}$$

where [C] is diagonal damping matrix with matrix coefficients of the following form:

$$[C] = [2 \cdot \omega_j \cdot \zeta_j] \tag{11}$$

where $\omega_j$ is j-th natural frequency, $\zeta_j$ effective damping coefficient of j-th vibration mode shape, $[\Psi]$ modal matrix. As a result of solving equation (10) displacements are determined, based on which strains, stresses, and forces of dynamic model can be also determined.

### Biomechanical model for modal and time-history analyses

The biomechanical model used to determine frequency response of human body to influence of vertical whole-body vibrations, developed for finite element analysis, is based on research of Kitazaki [4]. Spinal column, visceral column, head, torso segments, pelvis and buttocks tissue were modelled in the mid-sagital plane. Intervertebral connections were modelled as beam elements as well as vertebrae connections with mass elements corresponding to body weight loading each vertebrae in spinal column. Mutual connections of mass elements corresponding to visceral column as well as its connections with spinal column were modelled as spring elements. Head, pelvis and buttocks tissue were also modelled by beam elements. The damping effect is included through the use of effective damping ratio so called modal viscous damping at each vibration mode shape.

Biomechanical model of human body in normal sitting position developed for modal and time-history analysis by finite element method is shown in Fig. 2.

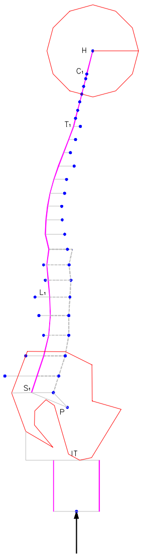

Fig. 2. Biomechanical model of human body in normal sitting position

## 3. RESULTS

Part of results of experimental research of vertical crane vibrations in working regimes, which were according to vibration analysis based on standard ISO 2631-1 and potentially critical for operator's health is shown in Fig. 3-5.

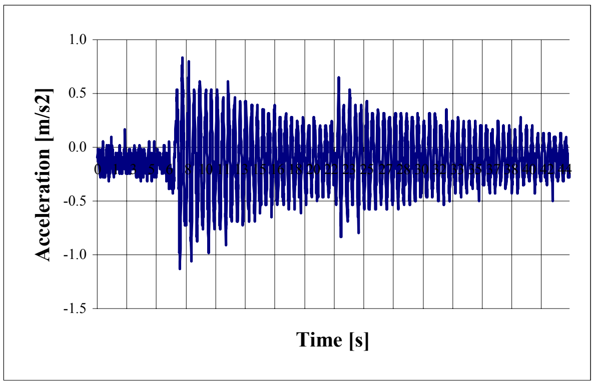

Fig. 3. Lifting load of 40 kN

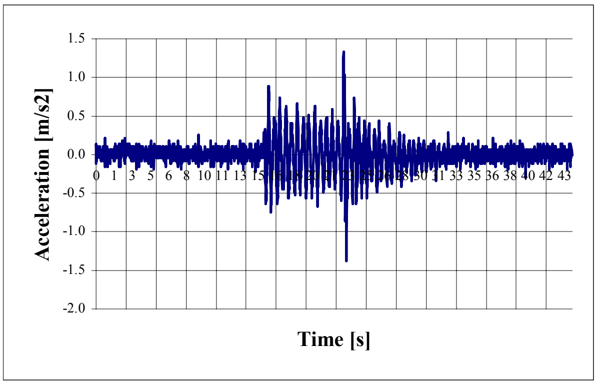

Fig. 4. Lowering load of 40 kN to the ground

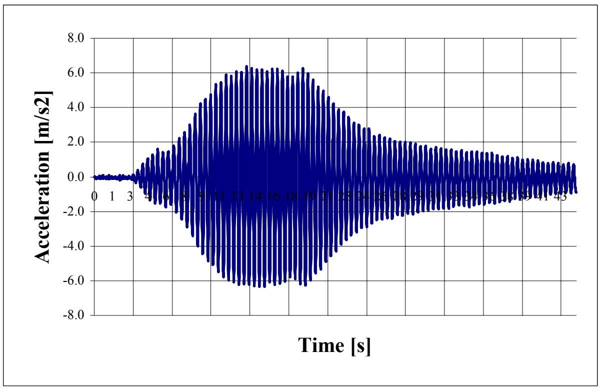

Fig. 5. Forced vibrations caused by periodic alternate vertical load of 10 kN

Results of third-octave band analysis of bridge crane vibration spectra, for considered working regimes, according to standard ISO 2631-1 are shown in Fig. 6-8.

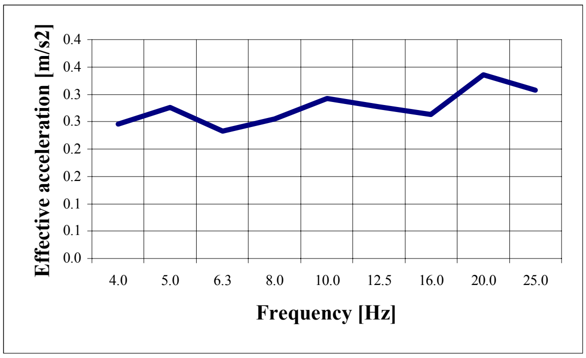

Fig. 6. Effective acceleration of one-third octave of bands vibrations when lifting load of 40kN

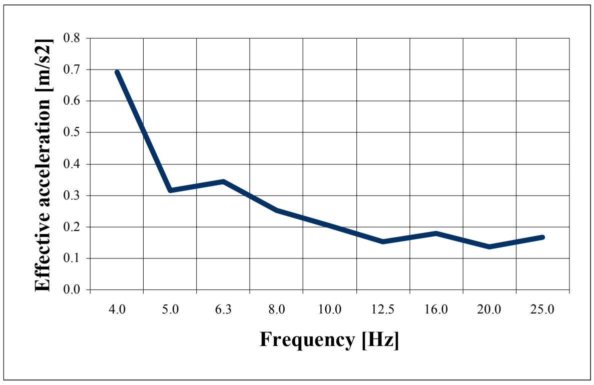

Fig. 7. Effective acceleration of one-third octave bands of vibration when lowering load of 40 kN

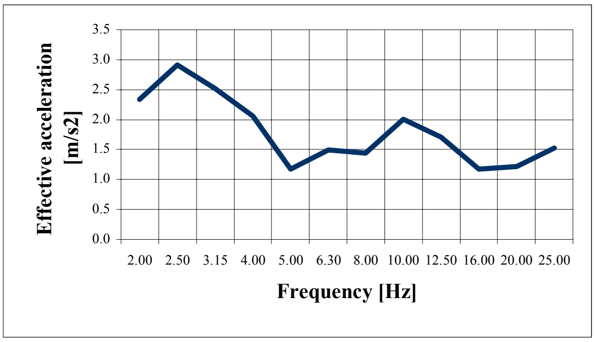

Fig. 8. Effective acceleration of one-third octave bands of vibrations caused by periodic alternate vertical load of 10 kN

Values of crest factor of considered working regimes are $f_{c1} = 3.32$, $f_{c2} = 7.76$ and $f_{c3} = 2.14$. Regarding obtained values of crest factor, which are less than 9, evaluation of influence of vibrations on health and working comfort of crane operator is based on overall effective acceleration of measured vibration spectra. Values of overall effective acceleration of measured vibration spectra, shown in Fig. 3-5, are $a_{w1} = 0.72$ m/s$^2$, $a_{w2} = 0.92$ m/s$^2$ and $a_{w3} = 5.24$ m/s$^2$.

Based on values of overall effective acceleration of vibration spectra, measured during research of bridge crane vibrations in chosen working regimes, the lower limit of exposure duration of people to influence of vibration spectra is determined. When exceeding this limit it is necassary to undertake certain preventive measures in order to decrease effects of vibrations. Likewise the upper limit of exposure duration of people to influence of vibration spectra to human body is determined. Exposure duration of people to influence of vibrations is not allowed to exceed this limit value. The determined values of exposure duration limits are: (3.5÷12) h for working regime shown in Fig. 3, (2÷6) h for working regime shown in Fig. 4, (0÷0.25) h for working regime shown in Fig.5. The influence of vibration spectra on working comfort of crane operator is also descriptively evaluated, namely, the one that is fairly uncomfortable for working regime shown in Fig. 3, uncomfortable for working regime shown in Fig. 4 and extremly uncomfortable for working regime shown in Fig. 5.

Results of analysis of influence of bridge crane vibrations, according to standard ISO 2631-1, on health of crane opertor reveal potential health harmfulness. That is why the modal and time-history analyses were conducted for chosen bridge crane working regimes. Spinal column is chosen as a part of human body through which whole-body vibrations are transfered to the rest of body. Thereby, occupational deseases caused by whole-body vibrations are mainly related to spinal column.

Frequency range of bridge crane vibrations, which is f = (1.5÷25) Hz, was obtained by analysis of investigation results. There was conducted modal analysis by finite element method based on biomechanical model, shown in Fig. 2, in order to find out natural frequencies of spinal column within frequency range of working vibrations. This analysis is conducted by means of software for finite element analysis ANSYS 5.3. Biomechanical model of human body in ANSYS environment is shown in Fig. 9.

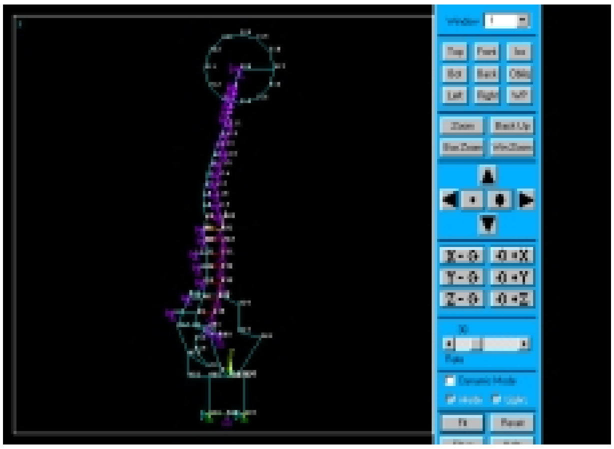

Fig. 9. Biomechanical model of human body in normal sitting position in ANSYS environment

By means of modal analysis, conducted by Block-Lanczos method, there were determined seventeen values of natural frequencies of spinal column within frequency range of working vibrations of bridge crane. Determined values of natural frequencies are given in Table 1.

Table 1. Values of natural frequencies of model

| MOD | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| [HZ] | 2.6 | 3.2 | 5.5 | 6.1 | 8.9 | 9.8 | 10.7 | 13.7 | 16.3 |
| MOD | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| [HZ] | 18.5 | 19.2 | 21.1 | 21.2 | 21.8 | 23.0 | 23.7 | 24.9 | - |

Some of determined vibration mode shapes are shown in Fig.10.

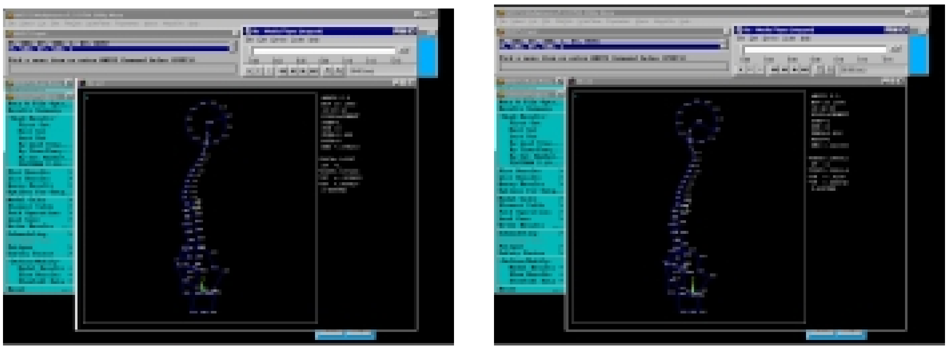

Fig. 10. 3rd and 6th vibration mode shapes at frequencies of 5.5 Hz and 9.8 Hz

By means of biomechanical model, shown in Fig. 2, there was conducted time-history analysis by finite element method, also in ANSYS environment, in order to determine load of each vertebra for different bridge crane working regimes. The following figures contain obtained results about load of fifth lumbar vertebra $L_5$ within period of time when the most severe vibrations were measured in chosen working regimes. This vertebra is chosen as a representative of lumbar part of spinal column which is usually exposed to degenerative changes caused by influence of vibrations and to pain caused by these degenerative changes.

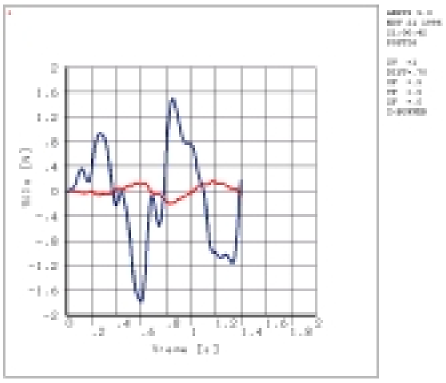

Fig. 11. Forces acting on vertebra $L_5$ in vertical and horizontal directions when lifting load of 40 kN

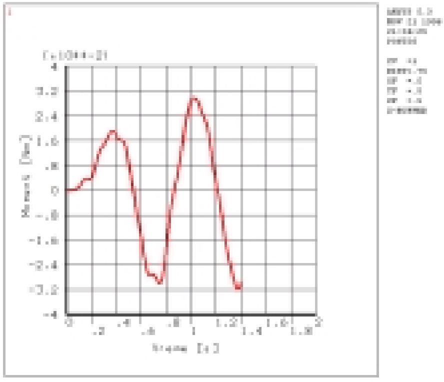

Fig. 12. Bending moment acting on vertebra $L_5$ when lifting load of 40 kN

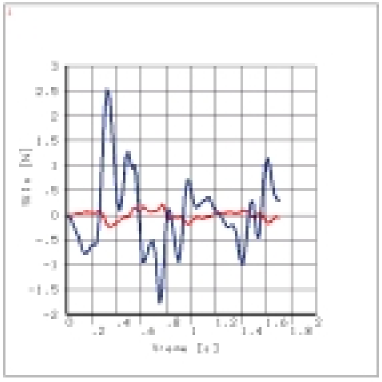

Fig. 13. Forces acting on vertebra $L_5$ in vertical and horizontal directions when lowering load of 40 kN

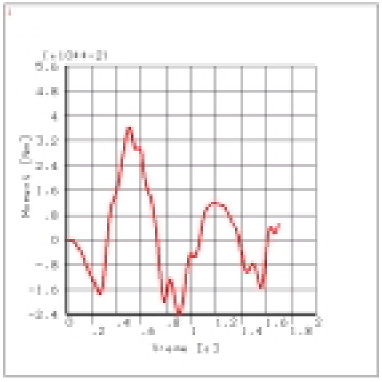

Fig. 14. Bending moment acting on vertebra $L_5$ when lowering load of 40 kN

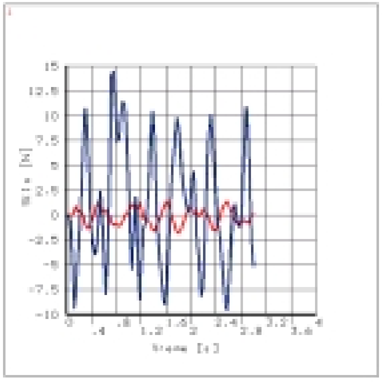

Fig. 15. Forces acting on vertebra $L_5$ in vertical and horizontal directions when acting periodic alternate vertical load of 10 kN

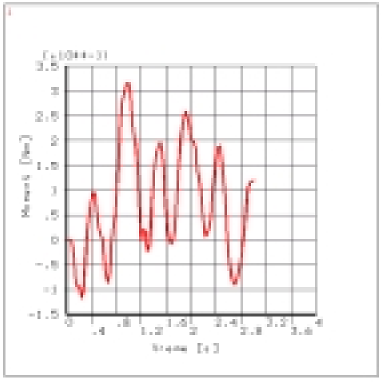

Fig. 16. Bending moment acting on vertebra $L_5$ when acting periodic alternate vertical load of 10 kN

## 4. DISCUSSION AND CONCLUSION

A very frequent problem related to low-back pain, as well as related to degenerative changes of vertebrae, caused by daily whole-body vibrations of operator of mobile machines, has not been considered important enough. This research, conducted on bridge crane with very elastic grinder, proves it. Results of analysis od vibration influence on human beings according to standard ISO 2631-1 reveal that daily exposure to vibrations caused by common working regimes may be harmful to the crane operator's health. For each of the three considered working regimes, the lower limit of exposure duration to influence of vibrations, namely, the limit which requires, if exceeded, certain preventive actions to be taken, is shorter than daily working hours. For the following working regimes: lowering load of 40 kN and forced vibrating caused by periodic alternate vertical load of 10 kN, upper limit of exposure duration to influence of vibrations that human beings can be exposed to is 6 hours and 15 minutes respectively. Regarding load capacity of bridge crane which is 50 kN, it is for sure that during common working regime such a lowering maximal load, upper limit of exposure duration of 6 hours (obtained for lowering load of 40 kN) would be significantly reduced. Vibrations caused by periodic alternate vertical load of 10 kN do not correspond to any common crane working regimes, therefore such vibrations could take place in situations caused by sudden lifting or lowering multiply bigger load.

Results obtained by analysis of influence of bridge crane vibrations on human beings according to standard ISO 2631-1 are expected regarding resonant frequency of human body which is within frequency range (4÷6) Hz [4]. For the following working regimes: lowering load of 40 kN and forced vibrating caused by periodic alternate vertical load of 10 kN, bridge crane severely vibrates within mentioned frequency range as shown in diagrams in Fig. 7 and 8.

There were determined natural frequencies of spinal column by modal analysis, which was also object of paper [7]; this analysis reveals even seventeen different natural frequencies of spinal column within frequency range of bridge crane working vibrations. Regarding this fact it is clear that bridge crane vibrations, because of resonant effect, cause additional load of operator's spinal column. Damping effect of human tissue, that vibrations are transfered through, significantly reduce influence of resonance; that is why this additional increase of spinal column load is less than it is expected to be.

Time-history analysis, that is also object of paper [8], is used to determine load of operator's spinal column caused by influence of bridge crane vibrations during different working regimes. There are shown vertical and horizontal forces, as well as bending moment in Fig. 11-16 acting on lumbar vertebra $L_5$ in chosen crane working regimes. Vertebra $L_5$ has been chosen as a part of spinal column bearing the most intense load caused by vibrations transferring to human body in sitting position. Determined magnitudes of load components of vertebra $L_5$, caused by vibrations, clearly reveal damping effects of human tissue that vibrations are transferred through to spinal column. Maximal magnitude of vertical force in regime of forced vibrating, caused by periodic alternate vertical load of 10 kN, is 15 N. Regarding load of vertebra $L_5$ of young person caused by its own weight and daily activities, that is 117.3 N [9], this additional load represents increase of 10% of common vertebra load.

With respect to possible harmfull effects of whole-body vibrations on health of opertors of mobile machines, as also stressed in the paper, this problem would be treated more carefully in rhe working machine design. Such approach would lead to certain constructive solutions reducing magnitude of vibrations which act on the working machines operator during different working regimes.

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# FREKVENTNI ODGOVOR KIČMENOG STUBA OPERATERA DIZALICE NA SLUČAJNU OSCILATORNU POBUDU

**Miomir Lj. Jovanović, Janko D. Jovanović**

*S obzirom na značaj koji vibracije imaju na zdravlje, radnu sposobnost i udobnost operatera radnih mašina, sprovedeno je istraživanje vibracija u različitim radnim režimima mosne dizalice. Na bazi rezultata mjerenja vibracija sprovedena je analiza njihovog uticaja na ljudsko zdravlje, radnu sposobnost i udobnost prema međunarodnom standardu ISO 2631-1. Za radne režime, koji su se prema ovoj analizi pokazali kao potencijalno kritični, sprovedena je analiza dinamičkog ponašanja kičmenog stuba operatera. Modalnom analizom su određene vrijednosti sopstvenih frekvencija i oblici oscilovanja kičmenog stuba, u frekventnom opsegu radnih vibracija, a vremenskom analizom opterećenje pojedinih pršljenova. Ljudski organizam je modeliran konačnih elementima, pri čemu su kičmeni stub, unutrašnji organi, glava, torzo, karlica i butine modelirani u uzdužnoj ravni konačnim elementima poput: grede, opruge i koncentrisane mase..*