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"RESEARCH AND DEVELOPMENT IN MECHANICAL INDUSTRY"

RaDMI 2009

PROCEEDINGS

Volume 1

Editor:
Predrag V. Dašić

1

16-19. September 2009.
Vrnjačka Banja, Serbia

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PREFACE

The First Conference "Research and Development in Chemical and Mechanical Industry" - **RaDMI 2001** was held upon the initiative of Predrag Dašić and prof. dr Miroslav Radovanović in Kruševac from October 22-24, 2001.

Until now 8 conferences were realized. The conference accepted and published over 1.500 papers, from which 1.100 were from abroad from 40 various countries of the world. Total number of authors and coauthors is over 2.000. Papers of the 8th conferences were published in 13 proceedings in hard copy and 8 proceedings in electronic form (CD-ROM). Number of printed material was approximately 11.000 pages. Some papers from the 8th International conference RaDMI 2008 will be printed in special issue of international journal from SCI-E paper "Strojniški Vestnik – Journal of Mechanical Engineering" Vol. 55, no. 2 (2009) (Web site: http://en.sv-jme.eu/).

Ninth International Conference "Research and Development in Mechanical Industry" **RaDMI 2009** will be held on 16 – 19th September 2009 in Vrnjačka Banja, Serbia.

Topics of the Conference RaDMI 2009 are:

- **Plenary Session:** Invitation papers, with 13 papers;
- **Session A:** Research and development of manufacturing systems, tools and technologies, new materials and production design, with 46 papers;
- **Session B:** Transport systems and logistics, with 12 papers;
- **Session C:** Application of information technologies in mechanical engineering, with 25 papers;
- **Session D:** Quality management, ISO 9000, ISO 14000, TQM and management in mechanical engineering, with 48 papers;
- **Session E:** Application of mechanical engineering in other industrial fields, with 49 papers.

The aim of organizing the Conference is: animating scientists from the faculty and from institutes and experts from the industry and their connecting and collaboration, and exchanging the experiences and knowledge of domestic and foreign scientists and experts.

On behalf of the organizers, we would like to extend our thanks to all organizations and institutions that have supported the initiative to have this anniversary gathering organized. We would also like to extend our thanks to all authors and participants from abroad and from the country for contribution to this conference.

Vrnjačka Banja, September 2009.

CHAIRMAN OF ORGANIZING COMMITTEE

Dašić P.

Predrag Dašić, prof.

CONTENTS

Volume 1

PLENARY SESSION (INVITATION PAPERS)

SESSION A
RESEARCH AND DEVELOPMENT OF MANUFACTURING SYSTEMS, TOOLS AND TECHNOLOGIES, NEW MATERIALS AND PRODUCTION DESIGN

C-
C-
C-
C-
C-
C

SESSION B
TRANSPORT SYSTEMS AND LOGISTICS

SESSION C
APPLICATION OF INFORMATION TECHNOLOGIES IN MECHANICAL ENGINEERING

Volume 2

SESSION D
QUALITY MANAGEMENT, ISO 9000, ISO 14000, TQM AND MANAGEMENT IN MECHANICAL ENGINEERING

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FATIGUE STRENGTH ASSESSMENT OF VIBRATION TRANSPORTER'S MOTOR CARRIER

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Summary: *Theoretical basics formulation of the implicit Newmark-method for numerical integration of dynamic motion equations is presented in the first part of this paper. According to theoretical assumptions, algorithms for the integration of dynamic motion equation are developed. Algorithms are implemented into the software package PAK. The second part of the paper shows the process of modeling the motor carrier, as well as the results of the analysis. Based on the results, the analysis and assessment of fatigue strength in the prescribed conditions of exploitation was carried out. Dynamic analysis of the motor carrier in the steady-state oscillation mode showed that the motor carrier has an unlimited working life.*

Keywords: *fatigue strength, FEM, implicit dynamic analysis*

1. INTRODUCTION

In practice, forces applied on constructions change during the time so displacement of material points depends on time. Construction motion is affected by inertial characteristics which have to be considered during motion calculation. Therefore, instead of static equilibrium conditions differential motion equations have to be set, whose integration leads to displacement, velocity and acceleration of specific construction spots. Such as in static analysis, finite element method has a significant implementation in the field of construction dynamics. Specific dynamic problems in practice are solved by using approximate implicit numerical integration method of dynamic motion equations.

This paper presents theoretical basics of implicit Newmark method. Then according to presented theoretical basics, algorithm for integration of dynamic motion equations is developed and implemented in PAK program package [1]. Section 3 of the paper shows the fatigue strength analysis of vibration transporter's motor carrier in prescribed conditions of exploitation. Detailed description of the problem is presented as well as the carrier modeling procedure and analysis results obtained by using presented theory which is implemented into PAK program package. Dynamic motor carrier analysis in the stable oscillation regime shows the carrier has an unlimited working life.

2. THEORETICAL BASICS

2.1. Differential motion equations

Using the virtual work principle $\delta A_u = \delta A_s$, differential motion equations of continuum divided into finite elements [2] are given in equation (1), Figure 1:

$$\int_V \sigma_{kj} \delta e_{kj} dV = \int_V F_j^v \delta u_j dV + \int_{S^\sigma} F_j^s \delta u_j dS + \sum_i F_k^i \delta u_k^i \tag{1}$$

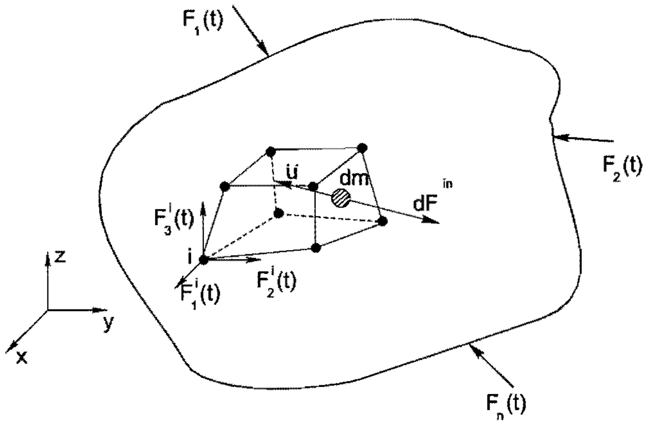

Figure 1: Forces applied on elementary finite element mass dm

Left side of the equation (1) represents virtual work of the internal forces:

$$\delta A_u = \int_V \sigma_{kj} \delta e_{kj} dV \,. \tag{2}$$

Right side of the equation (1) represents virtual work of the external forces:

$$\delta A_s = \int_V F_k^v \delta u_k dV + \int_{S^\sigma} F_k^s \delta u_k dS + \sum_i F_k^i \delta u_k^i , \tag{3}$$

In dynamic analysis inertial forces are added to volume forces $\mathbf{F}^V$ in the equation of finite element equilibrium. Elementary volume inertial force $d\mathbf{F}^{in}$ which corresponds to elementary mass dm is:

$$d\mathbf{F}^{in} = -\ddot{\mathbf{u}} dm = -\ddot{\mathbf{u}} \rho dV \,. \tag{4}$$

Substituting inertial force equation in relation (1) we get

$$\int_V \delta \mathbf{e}^T \boldsymbol{\sigma} dV = \int_V \delta \mathbf{u}^T \left(\mathbf{F}^V - \rho \ddot{\mathbf{u}} \right) dV + \int_S \delta \mathbf{u}_S^T \mathbf{F}^s dS \,. \tag{5}$$

Differentiating with respect to time of relation for displacement

$$\mathbf{u} = \mathbf{HU} \,, \tag{6}$$

we get velocity and acceleration for arbitrary material point

$$\dot{\mathbf{u}} = \mathbf{H}\dot{\mathbf{U}} \tag{7}$$
$$\ddot{\mathbf{u}} = \mathbf{H}\ddot{\mathbf{U}} \,. \tag{8}$$

Substituting equation (6) for $\delta \mathbf{u}$, in equation (5) follows

$$\delta \mathbf{U}^T \left(\int_V \mathbf{H}^T \rho \mathbf{H} dV \right) \ddot{\mathbf{U}} + \delta \mathbf{U}^T \int_V \left(\mathbf{B}^T \mathbf{C} \mathbf{B} dV \right) \mathbf{U} = \delta \mathbf{U}^T \mathbf{F} \tag{9}$$

wherefrom:

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{K}\mathbf{U} = \mathbf{F}(t) \,. \tag{10}$$

where $\mathbf{M}$ is finite element mass matrix, defined by the equation

$$\mathbf{M} = \int_V \rho \mathbf{H}^T \mathbf{H} dV . \tag{11}$$

Vector $\mathbf{F}(t)$ represents external forces applied on the finite element nodes, and comprises surface, volume, and concentrated forces depending on time.
In real materials appear damping forces proportional to material point velocity. Elementary damping force $d\mathbf{F}^d$ which corresponds to elementary volume dV is

$$d\mathbf{F}^d = -b\dot{\mathbf{u}}dV , \tag{12}$$

where b is dumping coefficient. Replacing equations for dumping force (12) in (5), as complementary volume force, by using (7), finite element equation of motion is obtained:

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{B}\dot{\mathbf{U}} + \mathbf{K}\mathbf{U} = \mathbf{F}(t) , \tag{13}$$

where $\mathbf{B}$ is dumping matrix,

$$\mathbf{B} = \int_V b \mathbf{H}^T \mathbf{H} dV . \tag{14}$$

Damping matrix $\mathbf{B}$ and mass matrix $\mathbf{M}$ have the same dimensions as element stiffness matrix $\mathbf{K}$, so the same procedure for matrix members organizing is used during forming mass matrix and dumping matrix of the construction.
Equations (11) and (14) define consistent mass matrix and consistent damping matrix. In order to save computer operating time, it is convenient to use lumped mass matrix, which contains members only on the main diagonal, instead of consistent mass matrix in the construction calculation with large number of degree of freedom. These members represent equivalent "concentrated masses". Construction mass matrix is in this case also diagonal so it is stored in the memory as vector of length equal to numbers of degrees of freedom.

2.2. Numerical integration methods of differential motion equations

Numerical methods of direct differential equation system integration have a wide usage in FEM and instead of analytical results for any moment of time t; they give results in discrete moments of time $0, \Delta t, 2\Delta t, \dots, n\Delta t$. Namely, we consider that the total period of time T is divided into n intervals $\Delta t = T/n$, within which we are interested in result of differential equation system. The procedure is based on searching the result in the moment $t + \Delta t$ at the end of the step according to the known result in moment t at the beginning of the interval Δt. Thereat, assumptions for change of displacement, velocity and acceleration within the interval Δt are introduced. These methods are often called step by step methods in the literature.

2.3. The Newmark method

Implicit methods mean fulfillment of differential motion equations at the moment $t + \Delta t$, so according to the known results at the moment t, unknown results are obtained at the moment $t + \Delta t$ and thus their fulfillment is certain and accurate. Choice of time step Δt in implicit methods is related to the desirable result accuracy and less to stability, since these methods can reach unconditional stability.
Implementation of Newmark method of direct system equation integration (10) or (13) is based on the assumption that generalized accelerations are constant in the time interval Δt, and that they can be written in the following way:

$$\ddot{\mathbf{U}}(\tau) = (1-\delta)\,{}^{t}\ddot{\mathbf{U}} + \delta\,{}^{t+\Delta t}\ddot{\mathbf{U}} , \tag{15}$$

where $\ddot{\mathbf{U}}(\tau)$ is acceleration at the moment $t \le \tau \le t + \Delta t$, further denoted as $\ddot{\mathbf{U}}$, $0 \le \delta \le 1$ is parameter, ${}^{t}\ddot{\mathbf{U}}$ and ${}^{t+\Delta t}\ddot{\mathbf{U}}$ are accelerations at the moment t and $t + \Delta t$. Here left superscript shows time moment that presented value it related to.
Integrating equation (15) in the interval Δt, we get:

$$^{t+\Delta t}\dot{\mathbf{U}} = {}^{t}\dot{\mathbf{U}} + \left[(1-\delta)\,{}^{t}\ddot{\mathbf{U}} + \delta\,{}^{t+\Delta t}\ddot{\mathbf{U}}\right]\Delta t\,, \qquad \textbf{(16)}$$

$$^{t+\Delta t}\mathbf{U} = {}^{t}\mathbf{U} + {}^{t}\dot{\mathbf{U}}\Delta t + \frac{1}{2}\left[(1-\delta)\,{}^{t}\ddot{\mathbf{U}} + \delta\,{}^{t+\Delta t}\ddot{\mathbf{U}}\right]\Delta t^2\,. \qquad \textbf{(17)}$$

In order to achieve better stability and result accuracy, instead of obtained equation (17) for $^{t+\Delta t}\mathbf{U}$, the following equation is used:

$$^{t+\Delta t}\mathbf{U} = {}^{t}\mathbf{U} + {}^{t}\dot{\mathbf{U}}\Delta t + \left[\left(\frac{1}{2}-\alpha\right){}^{t}\ddot{\mathbf{U}} + \alpha\,{}^{t+\Delta t}\ddot{\mathbf{U}}\right]\Delta t^2\,, \qquad \textbf{(18)}$$

where α is coefficient.

$$\delta \geq \frac{1}{2}; \quad \alpha \geq \frac{1}{4}\left(\frac{1}{2}+\delta\right)^2, \qquad \textbf{(19)}$$

In calculation, the most widely used

$$\delta = \frac{1}{2} \quad \alpha = \frac{1}{4}\,. \qquad \textbf{(20)}$$

Figure 2 shows approximation for speed $\dot{\mathbf{U}}$ that corresponds to the assumptions above. So, acceleration is constant in the interval Δt, corresponding to (15) and it is expressed through acceleration value at the beginning and end of time step. It is noticed that for $\delta = 0$ $\ddot{\mathbf{U}} = {}^{t}\ddot{\mathbf{U}}$, for $\delta = 1$ $\ddot{\mathbf{U}} = {}^{t+\Delta t}\ddot{\mathbf{U}}$, and for $\delta = 0.5$ $\ddot{\mathbf{U}} = \left({}^{t}\ddot{\mathbf{U}} + {}^{t+\Delta t}\ddot{\mathbf{U}}\right)/2$. Speed $\dot{\mathbf{U}}$ is linear function and generalized displacement $\mathbf{U}$ is square function in the interval Δt.
Newmark method is implicit so equation (13) is written for the moment $t+\Delta t$,

$$\mathbf{M}\,{}^{t+\Delta t}\ddot{\mathbf{U}} + \mathbf{B}\,{}^{t+\Delta t}\dot{\mathbf{U}} + \mathbf{K}\,{}^{t+\Delta t}\mathbf{U} = {}^{t+\Delta t}\mathbf{F} \qquad \textbf{(21)}$$

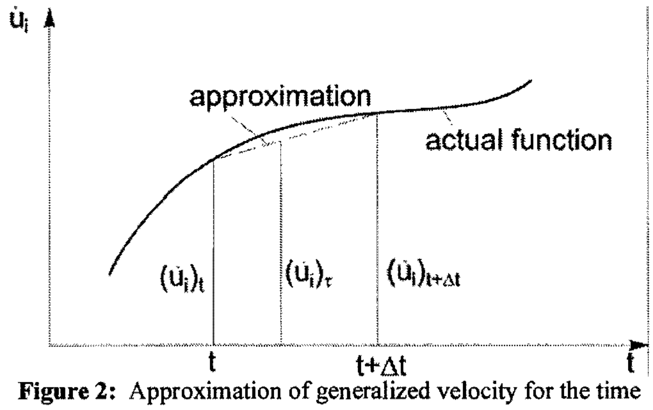

Figure 2: Approximation of generalized velocity for the time step

Further procedure is based on expressing the vector $^{t+\Delta t}\ddot{\mathbf{U}}$ through ${}^{t}\mathbf{U}, {}^{t}\dot{\mathbf{U}}, {}^{t}\ddot{\mathbf{U}}$ and $^{t+\Delta t}\mathbf{U}$ according to equation (18)

$$^{t+\Delta t}\ddot{\mathbf{U}} = \frac{1}{\alpha(\Delta t)^2}\left[{}^{t+\Delta t}\mathbf{U} - {}^{t}\mathbf{U} - {}^{t}\dot{\mathbf{U}}\Delta t - \left(\frac{1}{2}-\alpha\right)(\Delta t)^2\,{}^{t}\ddot{\mathbf{U}}\right] \qquad \textbf{(22)}$$

Then, $^{t+\Delta t}\dot{\mathbf{U}}$ is expressed, substituting equation (16) in (20), in the form:

$$ {}^{t+\Delta t}\dot{\mathbf{U}} = \frac{\delta}{\alpha \Delta t}\left({}^{t+\Delta t}\mathbf{U} - {}^{t}\mathbf{U}\right) - \left(\frac{\delta}{\alpha} - 1\right){}^{t}\dot{\mathbf{U}} - \left(\frac{\delta}{2\alpha} - 1\right)\Delta t\,{}^{t}\ddot{\mathbf{U}} \tag{23} $$

Finally , replacing final equations for ${}^{t+\Delta t}\ddot{\mathbf{U}}$ and ${}^{t+\Delta t}\dot{\mathbf{U}}$ in equation (21), we obtain system of algebraic equations with respect to unknown generalized displacements,

$$ \hat{\mathbf{K}}\,{}^{t+\Delta t}\mathbf{U} = {}^{t+\Delta t}\hat{\mathbf{F}} \tag{24} $$

which can be solved with respect to unknown displacements ${}^{t+\Delta t}\mathbf{U}$. Matrix $\hat{\mathbf{K}}$ and right side vector $\hat{\mathbf{F}}$ are:

$$ \hat{\mathbf{K}} = \mathbf{K} + a_0\mathbf{M} + a_1\mathbf{B} \tag{25} $$

$$ {}^{t+\Delta t}\hat{\mathbf{F}} = {}^{t+\Delta t}\mathbf{F} + \mathbf{M}\left(a_0\,{}^{t}\mathbf{U} + a_2\,{}^{t}\dot{\mathbf{U}} + a_3\,{}^{t}\ddot{\mathbf{U}}\right) + \mathbf{B}\left(a_1\,{}^{t}\mathbf{U} + a_4\,{}^{t}\dot{\mathbf{U}} + a_5\,{}^{t}\ddot{\mathbf{U}}\right) \tag{26} $$

where $a_0, a_1, \ldots a_5$ are coefficients

$$ a_0 = \frac{1}{\alpha(\Delta t)^2}, \quad a_1 = \frac{\delta}{\alpha \Delta t}, \quad a_2 = \frac{1}{\alpha \Delta t} $$
$$ a_3 = \frac{1}{2\alpha} - 1, \quad a_4 = \frac{\delta}{\alpha} - 1, \quad a_5 = \left(\frac{\delta}{2\alpha} - 1\right)\Delta t \tag{27} $$

It is noticed that in case of linear problem (system matrixes are constant) and during the same integration step, it is possible to factorize matrix $\hat{\mathbf{K}}$ only once, and then for each time step to determine right side vector ${}^{t+\Delta t}\hat{\mathbf{F}}$ as well as to efficiently get results using backward algorithm. Since factorization of matrix $\hat{\mathbf{K}}$ takes most time, this way computer operating time is saved. Time step choice affects result accuracy and stability, especially while solving nonlinear problems. In practice, time step is most often determined to be at least 20 times smaller than period that correspond to first eigen value, which means that analysis of eigen values should always be done first, and then, according to the obtained results take the time step.

3. EXAMPLE

3.1. Problem description

The aim of analysis is to check if the motor carrier satisfies fatigue strength in prescribed exploitation conditions.

3.2. Model description

Figure 3 shows the model discretized by 3D finite elements [3]. Construction half is modeled. The model is discretized with 17902 nodes and 10812 elements.

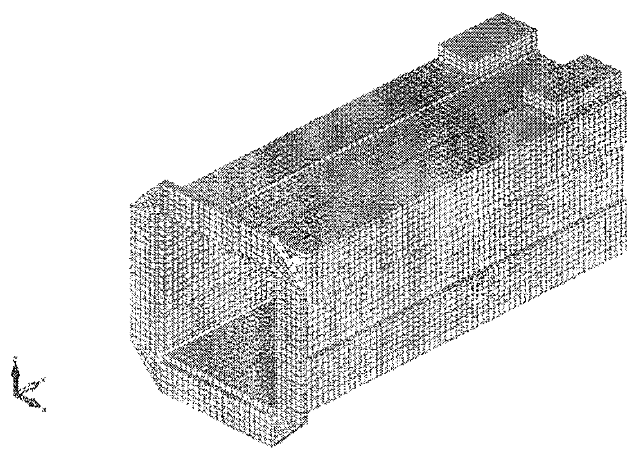

Figure 3: FE model – 3D finite elements

3.3. Boundary conditions

Boundary conditions include model symmetry, i.e. consider that half of the model is modeled. Symmetry plane is XZ so in all the nodes, marked on Figure 4, displacements in Y-direction are restricted.

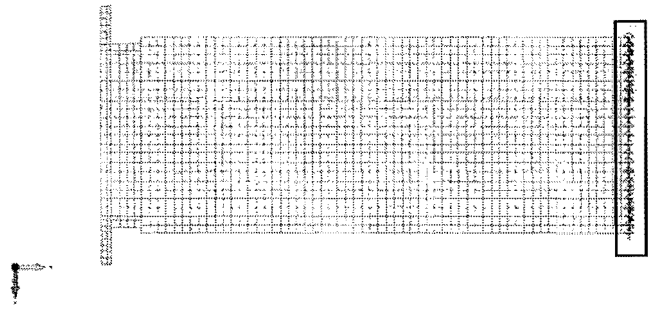

Figure 4: Boundary conditions of the model's symmetry

Boundary conditions due to connection of the modeled part with another part of construction are shown on Figure 5. Nodes matching the screw position restrict displacements in X-axis and Z-axis direction.

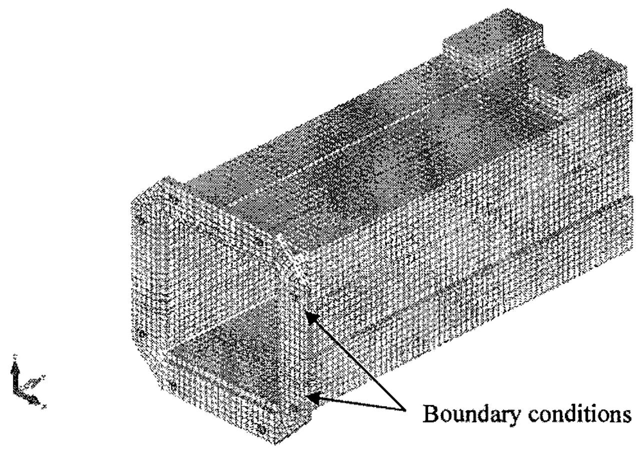

Figure 5: FE model – connection boundary conditions

3.4. Loads

Eigen mass of motor carrier is applied in the Z-axis direction. Motor mass, 3894.57N, is given in Z-axis direction through concentrated forces. Work moment, 196.2 Nm, is given through couple forces. Variable centrifugal force with amplitude

$$F = 105323\ N \tag{28}$$

is given through the functions:

$$F_x = F \cdot \cos(\omega t) \ \text{i} \ F_z = F \cdot \sin(\omega t) \tag{29}$$

where:

$$\omega = 102.6 \frac{rad}{s} \tag{30}$$

3.5. Determining dynamic analysis parameters

In order to determine value of the critical time step the eigen frequency analysis is done. The lowest eigen frequency is:

$$f_1 = 228Hz \quad \textbf{(31)}$$

Time step is determined as:

$$\Delta t = 0.0001 \leq \frac{1}{40 \cdot f_1} \quad \textbf{(32)}$$

3.6. Result review

Dynamic behavior of motor carrier is observed in the time step of 10.5s. Results are shown when motor carrier enters the stable working regime.

Figure 6 shows the field of total displacements at the moment 10.4312s, whereas figure 7 shows the diagram of total displacements in time step from 10.25 s to 10.5 s, i.e. in the stable working regime. Field of total displacement is shown for the node 13797, which represents the location of the maximum stress value.

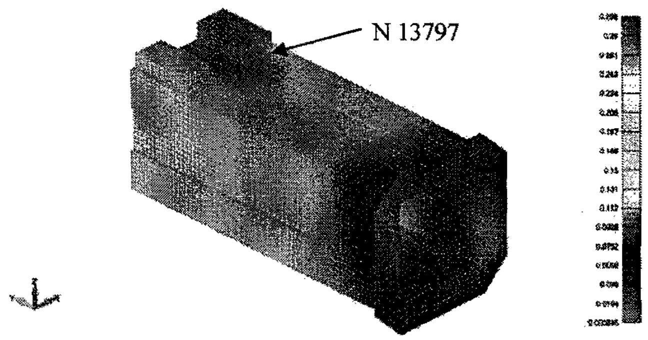

Figure 6: Total displacements in [mm], at the moment 10.4312s

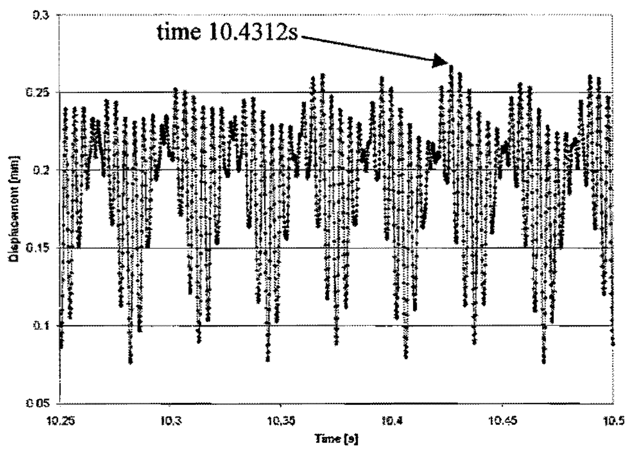

Figure 7: Total displacements in the node 13797

Figure 8 shows the equivalent stress field at the moment 10.4312s, whereas Figure 9 shows equivalent stress diagram at the time interval from 10.25 s to 10.5 s, i.e. in the stable working regime. Maximal stress value is in the element 8847.

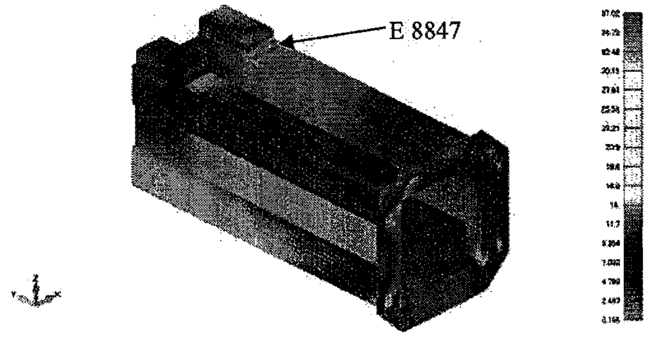

Figure 8: Equivalent stress at the moment 10.4312s

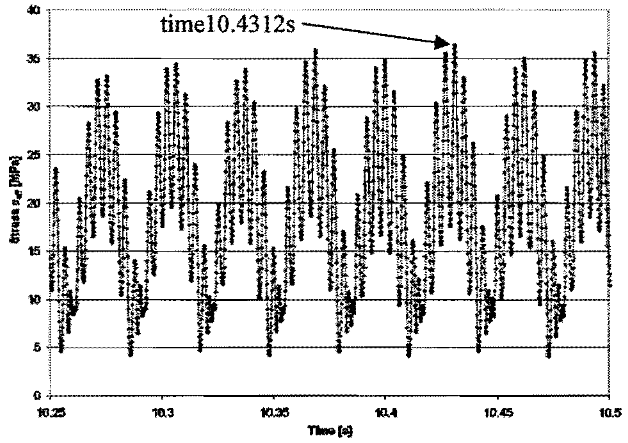

Figure 9: Equivalent stress in the element 8847

Figure 10 shows stress diagram σ_{yy} at the time interval from 10.25 s to 10.5 s, i.e. in the stable working regime.

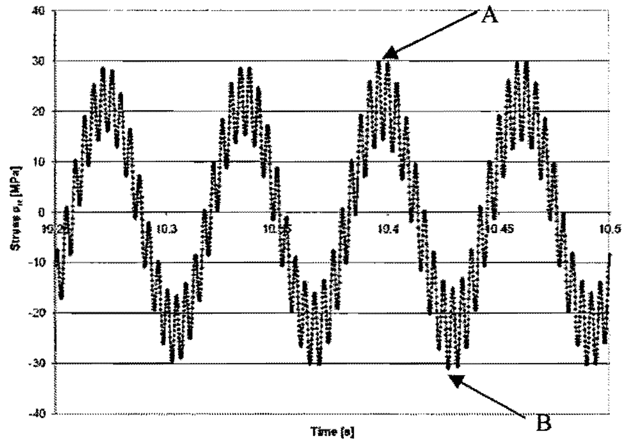

Figure 10: Stress σ_{yy} in the element 8847

3.7 Analysis of obtained results and estimation of long-term dynamic strength

Assessment of fatigue strength is done by applying the European standard – prEN 1993-1-9:2003 [4], according to table 8.1 (case 1) and chapter 7.1 of this standard, limit value of fatigue strength can be calculated $\Delta\sigma_L$:

$$\Delta\sigma_c = 160MPa \quad (33)$$

$$\Delta\sigma_D = 0.737\Delta\sigma_c \quad (34)$$

$$\Delta\sigma_L = 0.549\Delta\sigma_D = 64.7MPa \quad \textbf{(35)}$$

Analyzing the diagram from Figure 10, it can be observed that maximal difference between stress amplitudes (point A and B) is $\Delta\sigma_{yy} = 60.3$ MPa, which is less than fatigue strength value, 64.7MPa.

According to the analysis and in accordance with this standard, it can be concluded that motor carrier has an unlimited working life.

4. CONCLUSION

The aim of this paper is to solve specific dynamic problem using finite element method and implicit numerical methods of dynamic motion equation integration.

According to dynamic analysis of vibration transporter motor carrier in the stable oscillation regime and assessment of fatigue strength, in accordance with European standard – prEN 1993-1-9:2003, it is concluded that motor carrier has an unlimited working life.

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