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Design features of rubber metal compensators and numerical simulation of their stress-strain state upon hydrostatic compression

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A R T I C L E I N F O

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A B S T R A C T

This article discusses possibilities of application of widely applied and promoted abroad methods of active dampening of vibration and pressure oscillations (antinoise technology) in order to reduce vibration transfer via vibro-insulating couplings (compensators) of fluid pipelines. This is required in solution of issues of vibration insulation of equipment with regard to foundation and environment along pipelines with working mediums, for instance, in transporting of oil and gas, in energy and transport engineering. Reasonability of operation of active system in combination with means of passive dampening of these impacts is demonstrated. In terms of efficiency and minimum energy consumptions by active system it is reasonable to apply active dampening of vibration and oscillations downstream of the vibro-insulator (compensator) where their level is significantly lower than in the source. In the case of pipeline this implies dampening of vibration and oscillation downstream of compensator and damper, however, such works are nearly unavailable. This is attributed to significant coupling between vibration and pressure oscillation in compensator and pipeline itself, complicating solution of the problem. It is concluded that for efficient application of active dampening in pipeline compensators it is required to develop compensators with minimum coupling between vibration and oscillations.

1. Introduction

Development of up-to-date engineering and innovative approaches to improvement of designs and assemblies is directly related with the use of achievements at interdisciplinary and inter-industry level. Application of multilayer rubber-metal packages in rocket and helicopter engineering for supports in nozzle clusters of solid propellant rocket engines, helicopter bearings and engines of various floating

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crafts. Development of domestic composition of low modulus elastomers on the basis of polyisoprene made it possible to implement rubber metal absorbers operating in combination with dampening (difference between deformation work and elastic recovery in the form of hysteresis). Model of elastic 3D grid of vulcanizate acts as spring. Rubber vulcanizate should possess such elasticity modulus which depends on the value of deformation and not on its rate. Compensators with thin layer elements are radically new design of elastic couplings of pipeline. They are mainly aimed at decrease in vibration transfer from its source and at the same time at retention of displacement compensation upon vibration, impacts and oscillations. Low axial dimensions (in height) can displace structural resonances to high frequency range, which would permit to obtain significantly lower vibrational rigidity of compensators with thin layer runner metal elements (TRME) in comparison with rubber cord casing (RCC). The issues of vibration insulation of any object are related with determination of vibration transfer properties as frequency functions of rigidity of all structural elastic elements along height upon spatial motions (Kiryukhin, et al., 2011, 2013; Yablonskii, 2011; Tikhonov, et al., 2012; Chistyakov and Yablonskii, 2013; Ganiev, 1993, 2013; Kuznetsov, et al., 2011).

Stress-strain state is investigated using single method for rubber layer of various configuration. It is experimentally established that in thin layer under constrained deformation elastomer is a weakly compressed material. Low compressibility (Poisson coefficient = 0.4999) means that finite shear modulus or compressibility parameter can be written as***:*** $\boldsymbol{a}$ = G/K/10^{-3} –10^{-4}. The most dangerous in terms of tangential stresses are the points on internal surface of rigid element both in flat and spherical variants.

Axially symmetric design of rubber metal element is illustrated in Fig. 1 (Sobol & Statnikov, 2006; Lighthill, 1981; Lavrov, 1993; Martin & Smith, 2013; Reznichenko & Morozov, 2000; Khorolskii, 2010; Rozhnov & Shchitov, 2007; Zasypkin, 1995; Zaikov, 1991). The design is comprised of support rings (pos. 1, 2) and rubber metal package composed of a set of steel (plastic) plates (pos. 3), separated by layer of vulcanized rubber (with elasticity shear modulus of about 0.25 MPa) on the basis of synthetic rubber (polyisoprene, silicone, or polyurethane of elastic type). Selection of elastomer material is performed depending on operation conditions with regard to temperature range, environmental severity and impact pressure in internal cavity of technological object (ASTM D 429-81).

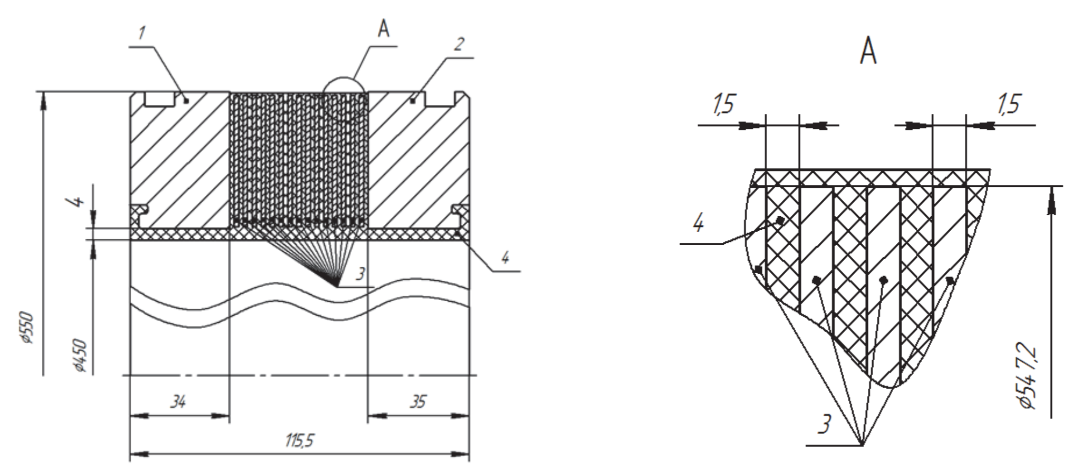


Fig. 1. Design of thin layer rubber metal element: 1, 2 – support rings; 3 – rigid elements; 4 – elastomer (vulcanizate) on the basis of polyisoprene

2. Numerical simulation of stress–strain state

Stress-strain state of TRME upon compression (at pressure P^{p}_{impact} and displacement of support rings by 40 mm) was simulated.

Geometrical model of TRME (Fig. 2) with mutually displaced axes of support rings is considered. Pressure is applied to internal surface of TRME and free edge "A" of support ring. Free edge "B" of other support ring is fixed in axial direction. In radial direction the TRME is fixed along the line L. The units of the edge A are connected by displacement coupling which presets equality of axial motions of these units (the edge "A" under pressure would remain parallel to the edge "B"). Finite element model of TRME is illustrated in Fig. 3.

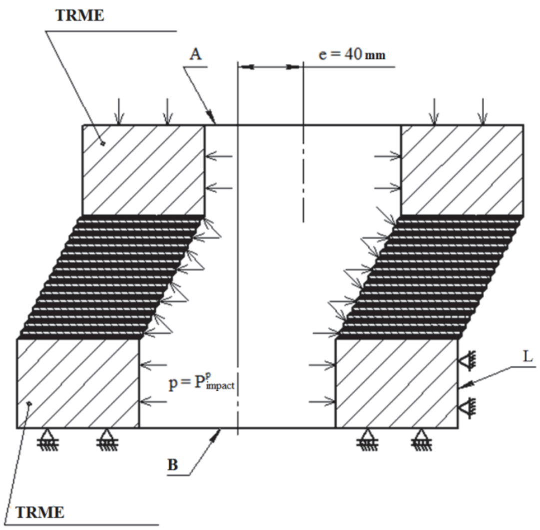


Fig. 2. Calculated diagram of hydrostatic load on TRME

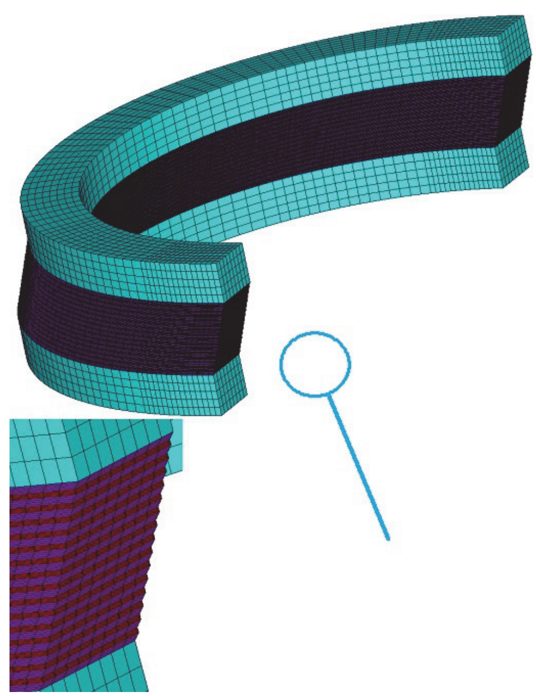


Fig. 3. 3D finite element model of TRME

Elastic boundary problem was solved by finite element method on the basis of variational approach. Equilibrium equation of continuous medium is as follows:

$$\vec{\nabla} \cdot \tilde{\sigma} + \rho \vec{F} = 0 \tag{1}$$
$$\vec{n} \cdot \tilde{\sigma}\big|_{\Gamma_F} = \vec{F}$$

Non-linear geometrical relations which determine stress-strain state of TRME are defined as follows:

$$\tilde{\varepsilon} = \frac{1}{2}\left(\vec{\nabla}\vec{u} + \vec{\nabla}\vec{u}^T\right) + \frac{1}{2}\left(\vec{\nabla}\vec{u} \cdot \vec{\nabla}\vec{u}^T + \vec{\nabla}\vec{u}^T \cdot \vec{\nabla}\vec{u}\right), \tag{2}$$

where $\tilde{\sigma}, \tilde{\varepsilon}, \vec{\nabla}\vec{u}$ is the tensor of stresses, strains and distortion; $\vec{n}, \vec{u}, \vec{F}$ is vector of normal, motions, surface force, respectively, $\vec{\nabla} = \vec{e}^{\,i} \dfrac{\partial}{\partial q^i}$ is the Hamiltonian.

Interrelation between stresses and strains is described by the generalized Hooke's law:

$$\begin{cases} \sigma_r = \dfrac{E}{(1+\mu_r)(1-2\mu_r)}((1-\mu)\varepsilon_r + \mu\varepsilon_\theta + \mu\varepsilon_z) \\ \sigma_\theta = \dfrac{E}{(1+\mu)(1-2\mu)}((1-\mu)\varepsilon_\theta + \mu\varepsilon_r + \mu\varepsilon_z) \\ \sigma_z = \dfrac{E}{(1+\mu)(1-2\mu)}((1-\mu)\varepsilon_z + \mu\varepsilon_r + \mu\varepsilon_\theta) \\ \sigma_{rz} = \dfrac{E}{2(1+\mu)}\varepsilon_{rz} \end{cases} \tag{3}$$

where E is the elasticity modulus, μ is the Poisson coefficient, $\varepsilon_r, \varepsilon_\theta, \varepsilon_z, \varepsilon_{rz}$ are the radial, circular, axial, and shear strains, $\sigma_r, \sigma_\theta, \sigma_z, \sigma_{rz}$ are the radial, circular, axial, and tangential stresses.

Equilibrium equation of finite element system in vector form is as follows:

$$[K]\{\delta\} = \{R\} \tag{4}$$

where $[K]$ is the matric of design rigidity, $\{\delta\}$ is the vector of unknowns, $\{R\}$ is the load vector. Matrices of finite element rigidity are determined by the following equation:

$$[k]^e = 2\pi \int_S [B]^T [D][B] r dS, \tag{5}$$

where $[B]$ is the geometrical matrix used for interrelation between strains and displacement in finite element depending on the type of finite element, $[D]$ is the elasticity matrix depending on the type of stress state. Nonlinear physic-mechanical and thermo-mechanical properties of plate materials are illustrated in Fig. 4.

3. Results of numerical simulations

Results of numerical simulation of distribution of TRME stress-stress state parameters are illustrated in Figs. (5-9). They actually predetermined possibility of development of new generation of compensators, their operation principle is provided by relaxation ability of low modulus elastomer on the basis of polyisoprene, plasticized by low molecular divinyl rubber with terminal functional groups. Shear modulus of the elastomer was calculated by experiment planning matrix with transitional vibration rigidity as output parameter. Comparative results of complex tests of items of rubber cord sleeves and rubber metal type are illustrated in Fig. 10.

Application of specially developed designs of rubber metal elements due to physicochemical properties of elastomer in combination with perfect system of fixation to rigid elements (support rings and intermediate plates) provides minimum coupling of pressure oscillations and vibrations, decreases vibration transfer via their structure by an order of magnitude in wider frequency range in comparison with compensators made of rubber cord casings.

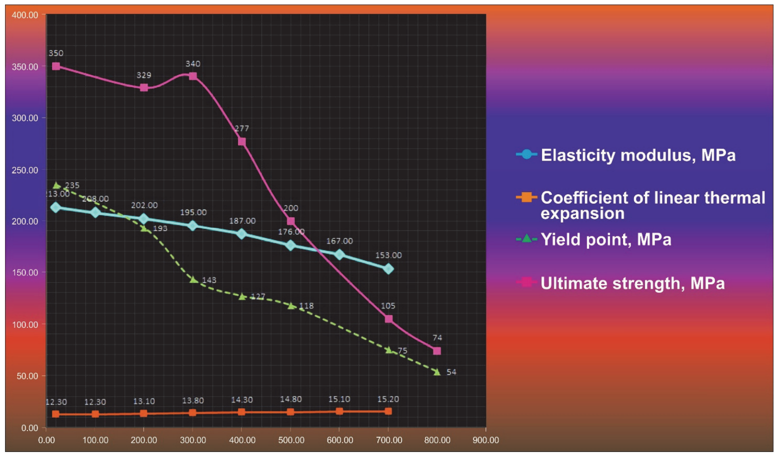


Fig. 4. Physico-mechanical and thermo-mechanical properties of plate materials as a function of heating temperature

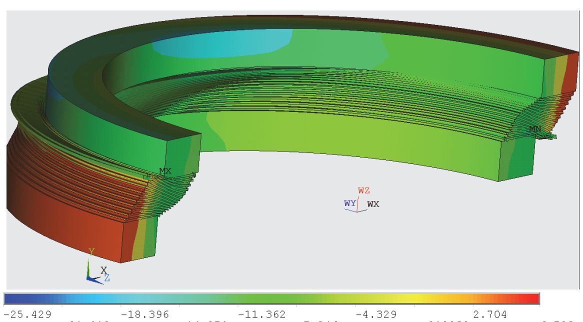


Fig. 5. Map of axial stresses σ_z , MPa, deformation scale 1:8

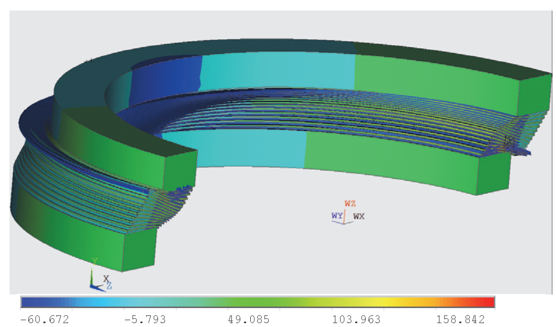


Fig. 6. Map of circular stresses σ_θ , MPa, deformation scale 1:8

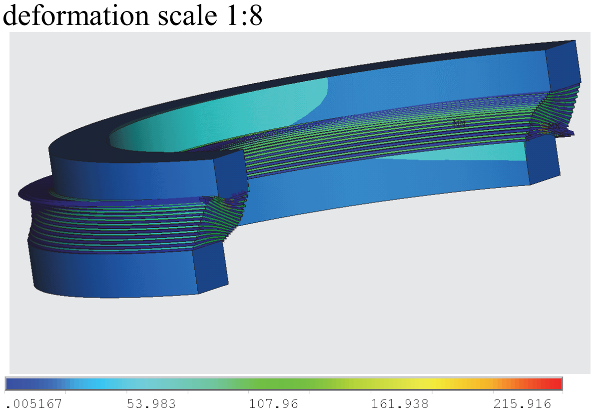


Fig. 7. Map of equivalent von Mises stresses , MPa, deformation scale 1:8

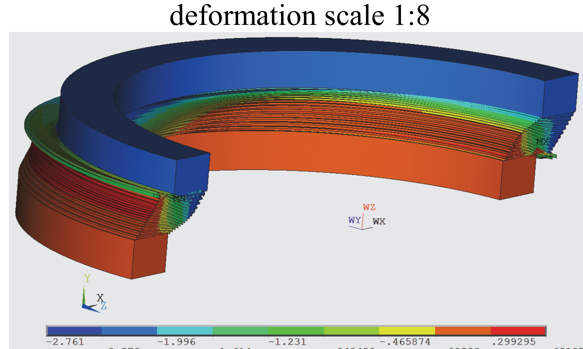


Fig. 8. Map of axial displacements , mm, deformation scale 1:8

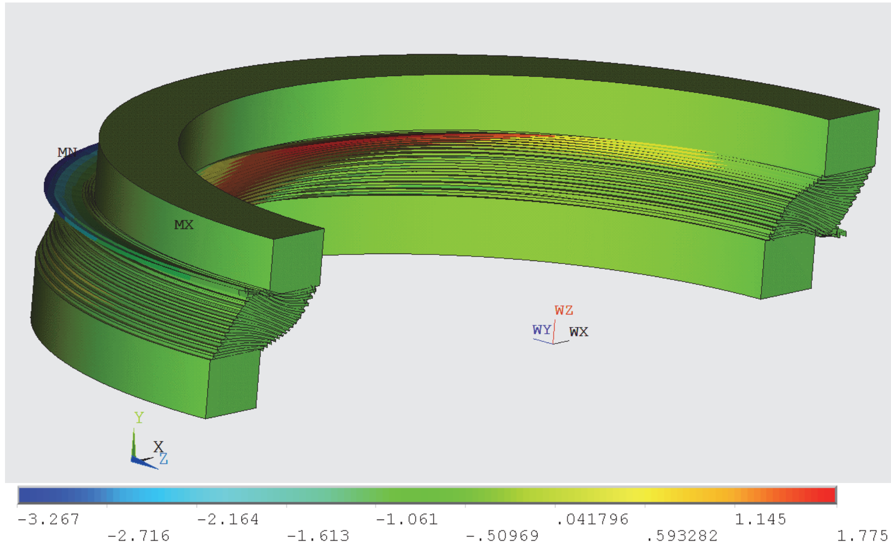
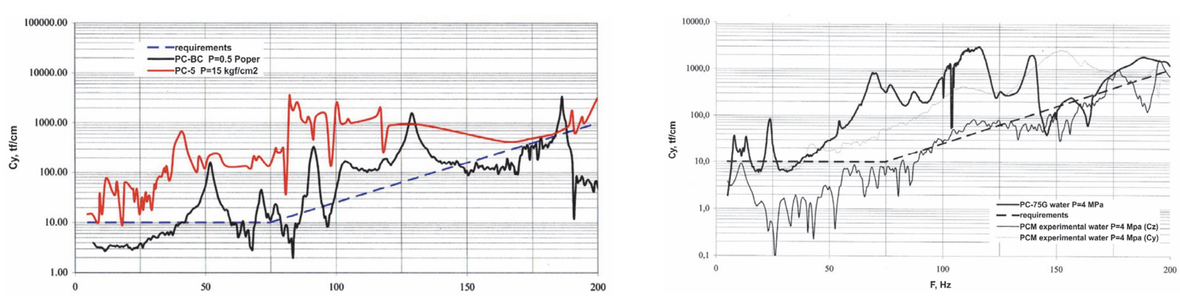


Fig. 9. Map of circular displacements u_θ , mm, deformation scale 1:8

4. Results and discussion

Our theoretical and experimental studies demonstrated that sharp increase in vibration rigidity with regard to static rigidity (at zero frequency) is observed with increase in vibration frequency for most existing compensators. Vibration rigidity (also known as mechanical resistance) is determined as the ratio of the dynamic force at compensator output to the vibration amplitude at its input (Popkov, 2009) at preset perturbation frequency. It characterizes vibro-insulating properties of compensator: the lower is the rigidity, the better is the vibro-insulation. Increase in rigidity can equal to tens and hundreds of starting from unities and tens of Hz. Figs. 10a and 10b illustrate examples of vibration rigidity for two different designs of high pressure compensators on the basis of rubber cord casings (RCC, upper curves). Engineering calculations and applied investigations make it possible to develop algorithms of similar designs for various industries as corner compensators, specialized compensators (for instance, instead of bellows compensators), vibration protection supports for machine and ventilation equipment. Light variants can be fabricated in the form of rubber plastic item.

Application of out specially designed compensators on the basis of thin layer rubber metal elements (TRME) with minimum coupling between pressure oscillations and vibrations due to special TRME design decreases vibration transfer along their structure by about an order of magnitude in wide frequency range (see Fig. 10 and (Sokolovskii et al., 2007)) in comparison with compensators with RCC. This facilitates to apply them as background upon development of system of active dampening of vibration and hydrodynamic noises in compensators of high pressure high diameter pipelines.



(a) (b)

Fig. 10. Comparison of rigidity of compensators, type 1 (a) and type 2 (b) with RCC (upper curve) and respective compensators on the basis of TRME of the same pressure and diameter

5. Conclusions

- Improvement of vibration insulation of commercial equipment with regard to foundation and environment along pipelines with working mediums, for instance, in transporting of oil and gas, in energy and transport engineering requires for development of methods and tools of wide band active dampening in couplings (compensators) of high pressure fluid pipelines.

- Development of such active vibro-insulating systems in compensators with fluid is complicated due to strong coupling between vibration and pulsation in compensator upon its vibrating deformation.

- In order to implement such active systems, it is required to develop compensators with minimum coupling between vibration and oscillations, possessing possibly minimum vibrational rigidity in wide frequency range in three directions.

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