Dynamic FE Analysis of the High-Speed Planetary-Motion Mixer UM-500

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Abstract

In the current paper the results of finite element non-linear mechanical analysis of the energy-saving high-speed planetary-motion mixer UM-500 are presented. The mixer is a system consisting of two milling chambers partly filled with substance to be milled. Milling chambers are in compound motion: rotation about vertical central axis and self-rotation about moving sloping axes. To perform dynamic analysis detailed finite element model is created based on CAD model. Finite element model considers nearly all features of the real construction. By means of LS-DYNA the detailed finite element analysis of dynamic non-linear process of mixer takeoff out of the casing in the result of emergency situation is performed with use of elasto-plastic material model with strain-based failure criterion. Dynamic analysis of the rigid-body motion stability of the mixer at speed-up regime is carried out for simplified mathematical models

Introduction

In common life in various areas of industry (chemical, pharmaceutical) it is often required to transform large pieces of some substance into small ones. This process is called milling. Milling became widely used in chemical industry in the beginning of 20-th century. It is explained by progress in this field and appeared potential to create mixers or milling machines. Milling process is of great importance for today’s industry.

At present time new milling processes techniques require much from milling machines and their characteristics. Betterment of existing milling machines characteristics and design development of new models requires complex mechanical analysis enabling to evaluate kinematical characteristics, stresses, natural frequencies and other mechanical values; and also locate weak points and carry out design optimization of separate units and components.

For a long time mechanical analysis of mixers and milling machines was performed by means of experiments and simple analytical estimations. However, experimental way of analysis is costly enough as it requires few dozens of pre-production models before mass-production or even cannot be used at all. Besides, it should be noted that experimental research gives ability to control data in several dozens of points while during numerical simulation information can be obtained for every point. At the same time analytical research is not adequate enough to get correct and useful data.

Finite element (FE) analysis – numerical simulation is a widely recognized and verified method that is successfully applied during development of competitive high-tech devices by world leading companies. FE analysis based of LS-DYNA [1] enables to solve complex 3D mechanical problems with contact interaction, physical (material properties) and geometrical (finite strains) non-linearity in a reasonable time (hours or days).

In the current paper the procedure and results of FE analysis of several mechanical problems of high-speed milling machine – planetary-motion mixer UM-500 are presented.

General view of UM-500 is presented in Figure 1. Operating part of the mixer represents the system with two milling chambers partly filled with material to be milled (see Figure 2). Mixer UM-500 is used to mill large quantities of organic materials for food and pharmaceutical industry.

Figure 1. General view of the UM-500

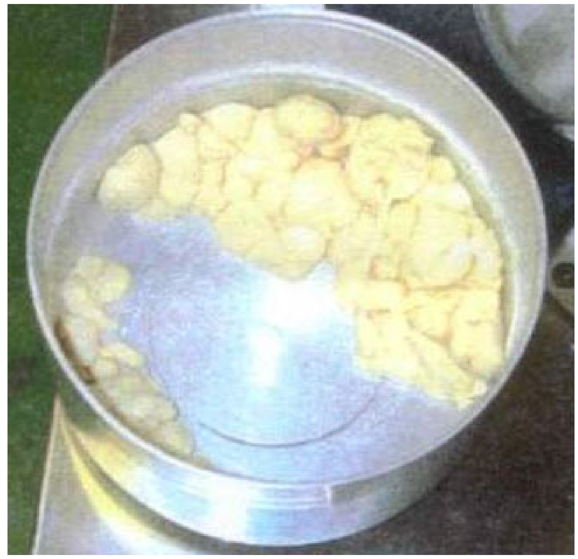


Figure 2. Milling chamber with substance

By kind of motion UM-500 can be classified as planetary-motion, because it is characterized by several milling chambers installed onto the vertical planet carrier. Planetary-motion mixer was firstly suggested in 1896 by US engineer A. Herzfild [2] and laboratory tests had shown that this type of mixers is more efficient then other existing. Principle of UM-500 operation is the following. Rotation is transferred from engine to the planet-carrier by means of belt transmission. Milling chambers are rotating together with planet carrier and get additional rotation around own axes by 2-level gearing. Rotation of milling chambers around vertical axis causes centrifugal forces field whose strength is several dozens times as great as gravity force strength. Under the action of centrifugal forces particles of the substance to be milled are thrown away to maximum distance from the planetary-carrier axis of rotation. Due to the own rotation of milling chambers particles are drawn into complex relative motion. During the motion they are milled due to impact with other particles and chamber wall and abrasion.

General characteristics of the mixer UM-500 are the following: angular velocity of the planet-carrier – 900 rpm, angular velocity of the milling chambers – 225 rpm, maximum capacity of the milling chambers – 5 kg, speed-up time – 1 min, mass of the construction – 315 kg.

Kinematical scheme of the mixer is presented in Figure 3. Figure 4 illustrates mixer cross-section. Mixer is placed into the larger section of the casing and fastened with it by bolt connection. Smaller section of the casing is occupied by engine. Casing is made of steel sheets and plates of 2 mm thickness. Casing has 6 legs and is placed on the floor.

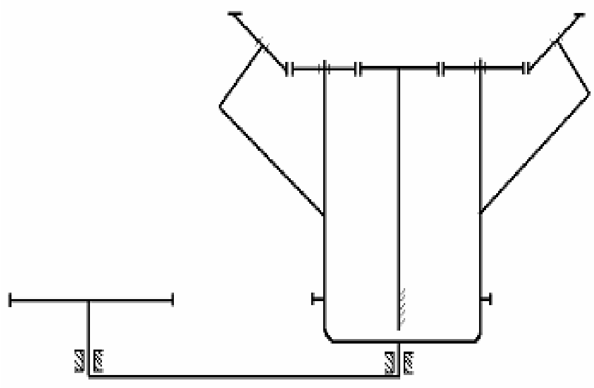


Figure 3. Kinematical scheme of UM-500

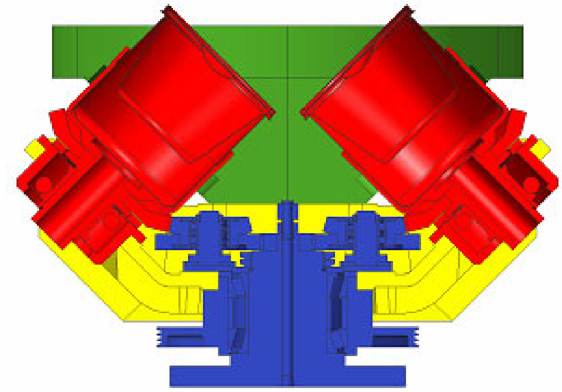


Figure 4. Mixer cross-section

UM-500 contains the following basic elements (see Figure 4):

- Foundation (blue part in the figure) that contains two parts: stable and rotating. Stable part connects mixer and casing, while rotating part transfers rotation. Parts are connected by means of bearing connection;
- Planet-carrier (yellow part in the figure) fastened to the rotating part of the foundation;
- Milling chambers (red parts in the figure) placed in special holes in the planet-carrier and connected with it by means of bearings. Milling chambers are also connected with stable part of the foundation by mean of gearing;
- Housing (green part in the figure) for primary defense from departing substance of milling chambers elements in case of breakdown.

Stability Analysis

During the first test of the UM-500 physical prototype the company developing the mixer design has faced the problem of critical vibrations that occur during the speed-up. One of the most likely reasons for vibrations is the movement stability loss. It is commonly known from the literature on analytical dynamics [3, 4] that there exists a theorem stating that free rotation of the rigid body around the medium principal inertia axis is instable. In the case of rotation of the body on elastic foundation the motion can be unstable as well, depending on the relation of foundation stiffness/angular velocity. These facts are well known, but there exist hardly any illustrations of the motion stability loss.

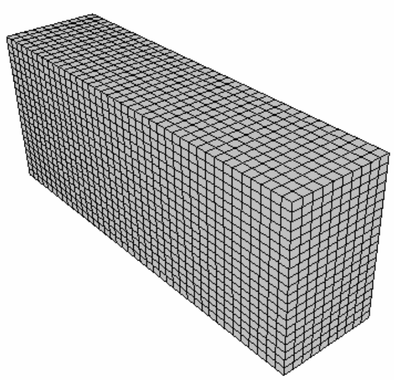
It is obvious that in case of considering real object - mixer UM-500, the conditions of the motion stability are much more difficult as it is not rigid, but elastic. In addition to it, mixer should be considered as gyrostat as the milling chambers are rotating around the local axis. Nevertheless, it seems to authors that considering simple models enables to analyze some principal effects and confirm the possibility of mixer rotation stability loss. Moreover, LS-DYNA rigid body powerful capabilities [1, 6] enable one to simulate the motion of the body with low computational expenses in a short time.

At the first stage of research the problem was solved about free rotation of the rigid parallelepiped around medium principal inertia axis. The mass and inertia characteristics of the parallelepiped were chosen close to those of mixer UM-500: mass and moments of inertia of real object are estimated and the geometrical parameters and density of the parallelepiped are calculated.

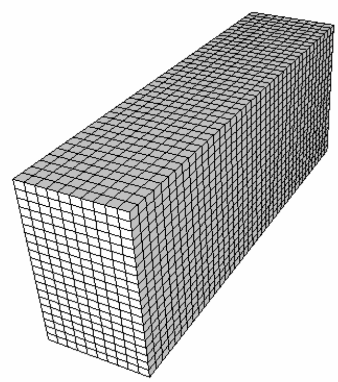
Stability loss in the real object is usually caused by some existing imperfection like mass misbalance, gap in connections, etc. During the numerical simulation to obtain the non-stable solution it is necessary to bring in some initial imperfection to the model. In the current paper imperfection were set in the following way: initial rotational velocity of the parallelepiped was set to $\omega = \omega_1 =$ 94 rad/s = 900 rpm around Oz_1. Angles that characterize rotational axis Oz_1 lean from vertical axis Oz in two perpendicular planes are denoted by α and β and their values are set to $\alpha = \beta =$ *10'*. Positions of the parallelepiped in different moments of time are presented in Figure 5. In Figure 6 the graph of point A coordinates vs time is shown. One can easily see from these figures that motion of the body is instable. It is possible to observe the following stages of the body motion:

- motion becomes instable at $t_1 = 0.2$ s;
- from $t_1 = 0.2$ s till $t_2 = 2.6$ s instantaneous axis of rotation changes its position in space. As a result, the parallelepiped turn out to be rotated by 180° relative to Oxy;
- from $t_2 = 2.6$ s till $t_3 = 3.2$ s the body rotates around medium moment of inertia axis;
- motion becomes instable again at $t_3 = 3.2$ s.

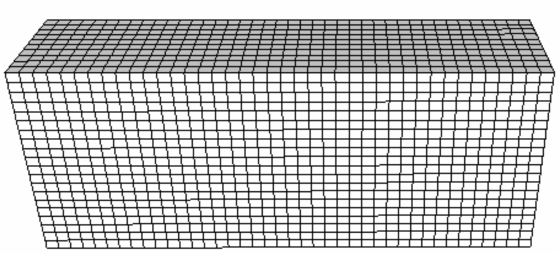
Figure 7 illustrates spatial curve - trajectory of Point A and its projection to *Oxy* plane. This projection is similar to herpolhode - curve that can be found in literature [7].



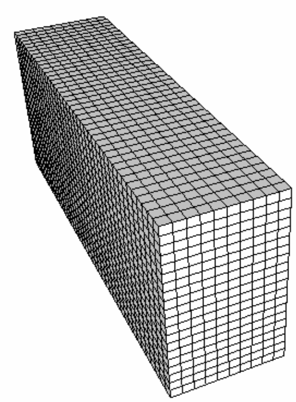
T = 0 s



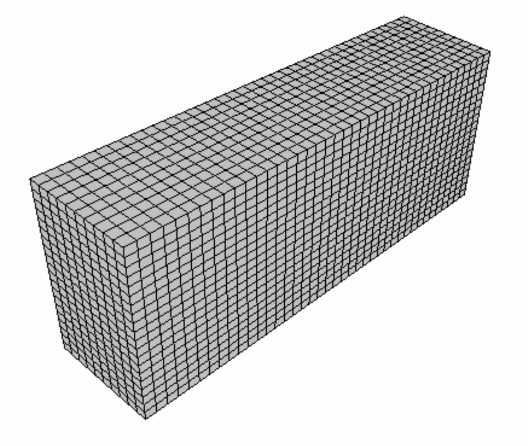
T = 0.2 s



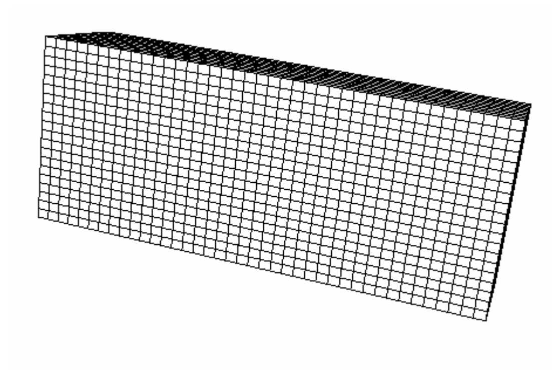
T= 0.4 s



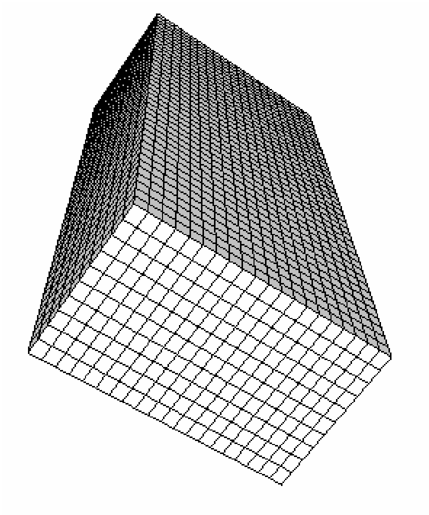
T = 0.6 s



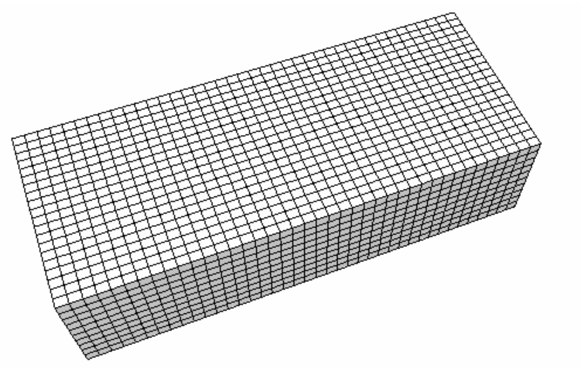
T = 0.8 s



T = 1.0 s

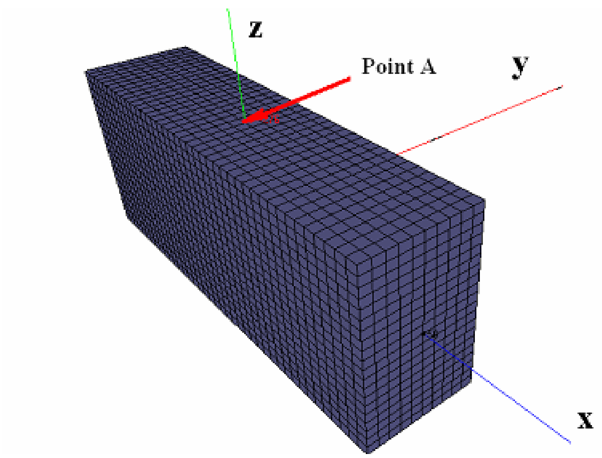


T = 1.2 s



T = 1.4 s

Figure 5. Non-stable motion of the rigid body



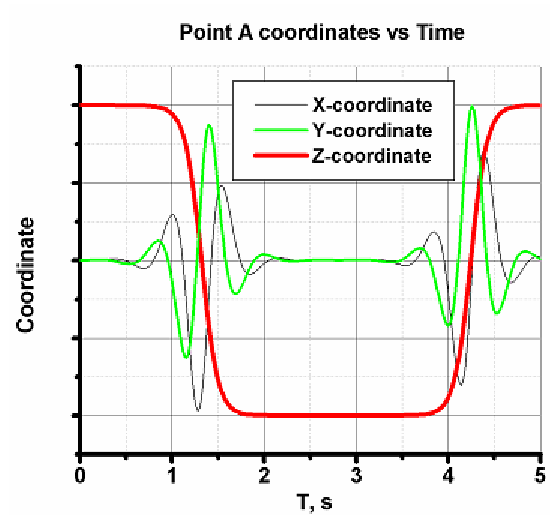


Figure 6. Point A displacements

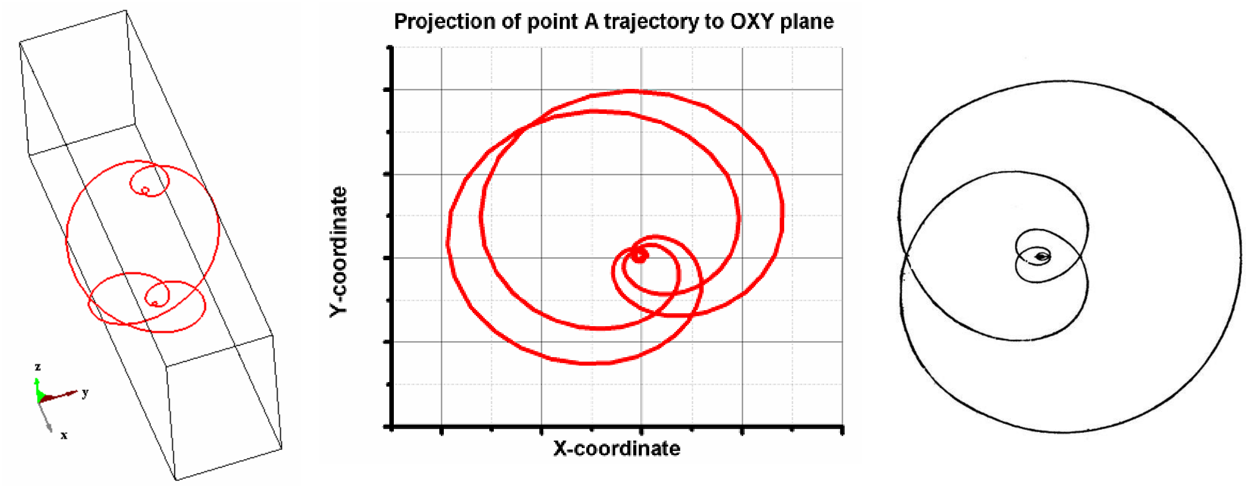


Figure 7. Point A trajectory. Herpolhode

Thus, the rotation of rigid body around the medium principle inertia axis is not stable and it can be shown with use of LS-DYNA. Analysis of the rotation around two other principal inertia axes was also performed with the same initial imperfections, and it was obtained that during T=20s motion keeps its stability, while rotation around the medium principle inertia axis becomes instable at $t_1 = 0.2$ s.

It should be noted that it is very important to control total kinetic energy of the system during simulation. Due to numerical computation finite rotation affects the kinetic energy of the considered conservative system growth significantly [5] and it can be kept within the required range just by reducing time step manually.

At the second stage of the motion stability analysis we considered a simplified model of the mixer - gyrostat on the elastic foundation. Mixer body was simulated by rigid parallelepiped and milling chambers by rigid cylinders. Mass and inertia characteristics of the parallelepiped and cylinders were chosen close to those of mixer UM-500.

Elastic foundation is simulated by elastic beam, and its parameters are estimated in the following way: modal analysis of the UM-500 model was carried out and based on its results two natural frequencies were found corresponding to mixer oscillations as a rigid body. Based on these natural frequencies values and mass of the mixer the stiffness of the beam was chosen and its geometrical parameters were calculated.

The speed-up of the construction is simulated: $\omega_{mixer} = 1.6*t$ rad/s; $\omega_{milling\ chamber} = 0.4*t$ rad/s. Rotation of the milling chambers was set around local axis with use of LS-DYNA option *BOUNDARY_ PRESCRIBED_MOTION_RIGID_LOCAL. Initial 9 seconds of the process were simulated before complete loss of stability (see Figure 10).

Deformed state of the construction at moment t=9 sec is shown in Figure 9. Analyzing the motion of the construction after t = 8 s oscillations with the growing amplitude can be observed transferring into subsequent chaotic motion (from t=8.9 s).

In spite of the simplicity of the considered mathematical model of the mixer it is possible to conclude that rotation stability loss is very likely and the construction should be redesigned to avoid such problems.

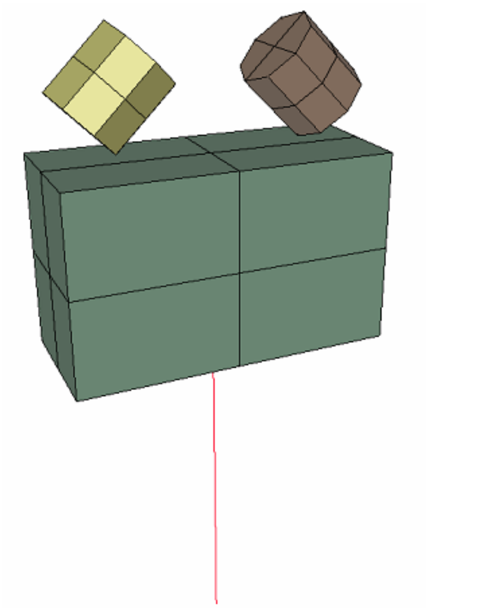


Figure 8. Simplified FE model of mixer

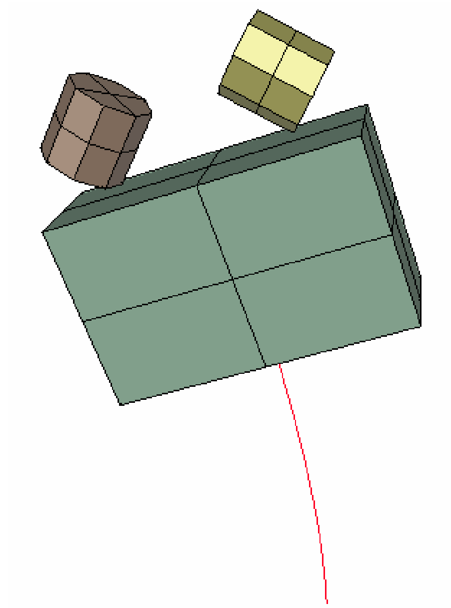


Figure 9. Stability loss

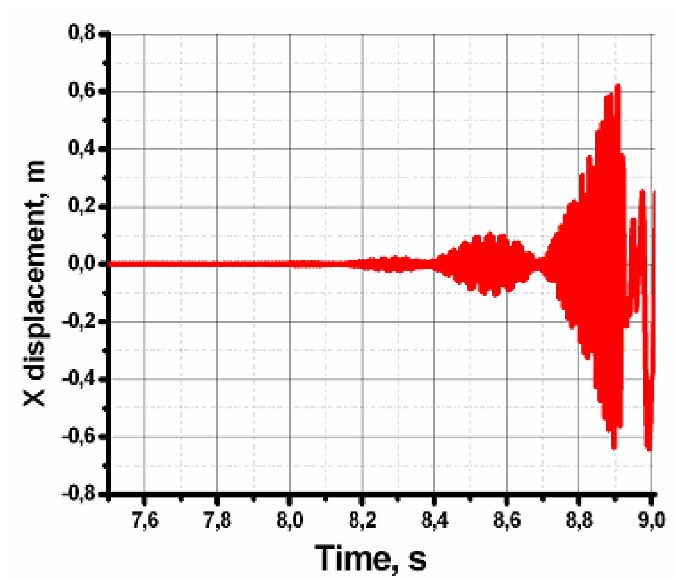


Figure 10. Horizontal displacements of the Point A. Loss of stability

Failure Analysis

During the operation of UM-500 mixer emergency case can happen. Due to unbalanced mass in milling chambers or loss of the motion stability critical vibrations can originate with following damage, elements break and departure out of the casing. During simulation it is assumed that all rotating kinetic energy of the body due to the emergency is converted into translating kinetic energy. Initial linear velocity $\mathbf{V}_0$ applied to the mixer is calculated based on the energy conservation law: $E_k = \frac{1}{2}\omega \cdot \mathrm{A} \cdot \omega = \frac{1}{2} \mathrm{m}\, \mathrm{V}_0 \cdot \mathrm{V}_0$, where $\boldsymbol{\omega}$ - angular velocity of the mixer; $\mathbf{V}_0$ – translation velocity of the mixer; A – inertia tensor of the mixer; m – mass of the mixer. The value of $\boldsymbol{\omega}$ is taken equal to 600 rpm. In this case $\mathbf{V}_0$ is equal to 25 m/s. This value of $\mathbf{V}_0$ allows simulating the "worst" case of emergency. In this case the damages caused by the mixer rush-out will be greatest of ever possible.

When simulating emergency it is assumed that due to the misbalance of the construction the critical vibration of the mixer appears. In this situation the damage can occur in the bolt connections of the mixer and casing. In this simulation it is assumed that the whole mixer is rushing out the casing. This also simulates the "worst" case.

To simulate emergency case LS-DYNA FE software was used. During the simulation four linear elasto-plastic materials with ε-based failure criterion were used in this model (MAT_PLASTIC_KINEMATIC). Complete FE model of the high-speed mixing machine was created to perform dynamic non-linear simulation of the emergency situation – rushing of the mixer out of the casing. Automatic contact algorithms are utilized to describe contact interaction of the construction parts. The FE model contains all mixer elements: planetary-carrier, housing, milling chambers, tooth gears, motor and casing (see Figure 11).

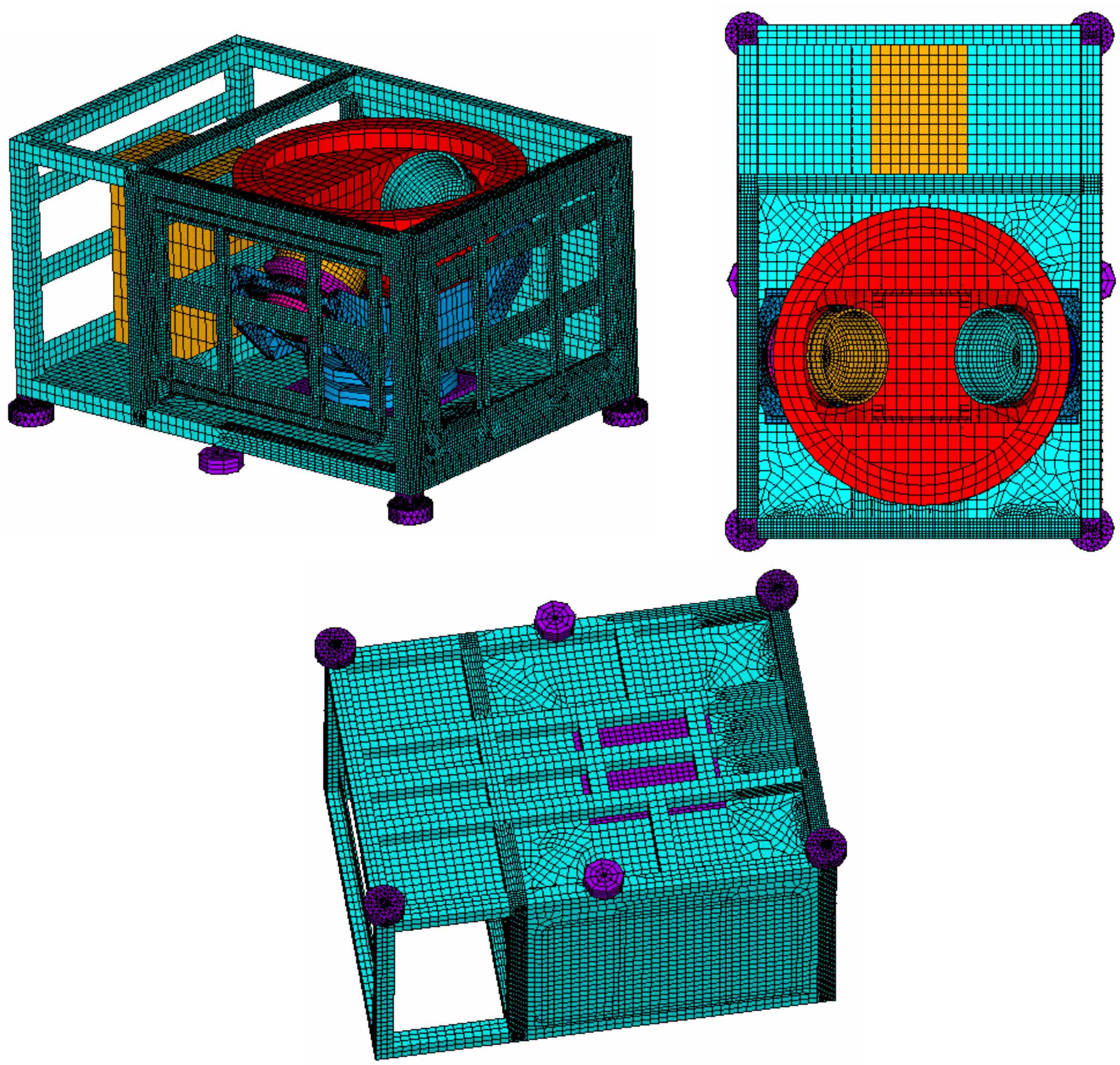
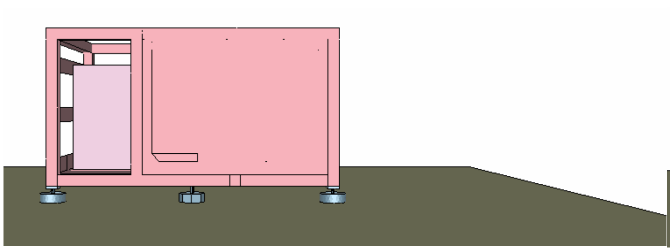


Figure 11. Full FE model of the mixer UM-500

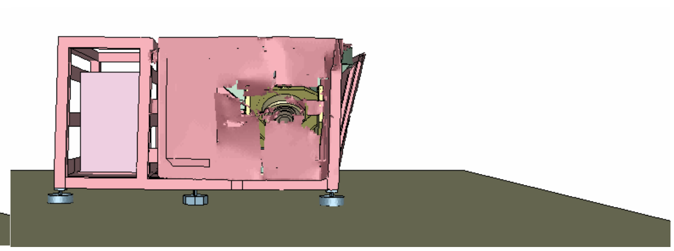
General characteristics of the FE model:

Number of nodes		96 889
Number of elements		
	Solid	37 919
	Shell	58 970
Number of equations		290 667

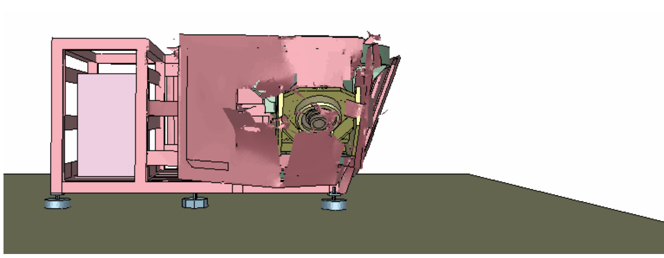
In order to analyse in details the emergency case, 7 various problems were solved. Two main parameters were being varied: angle of the mixer rushing-out α and coefficient of friction between legs and floor μ. In Figures 12, 13 the deformed state of the construction vs. time for the whole structure is presented for the case of α=45° and μ=0.5. Pictures should be analysed from left to right and from top to bottom.



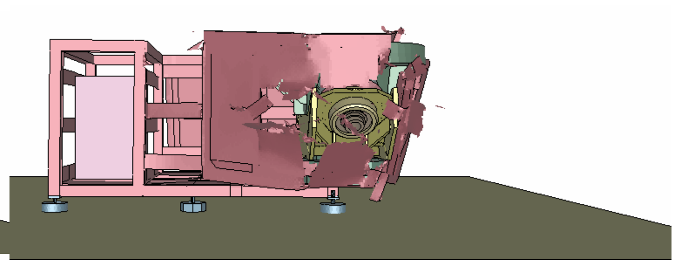
0 s



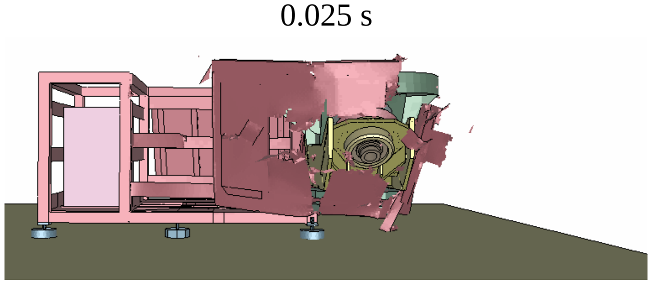
0.015 s



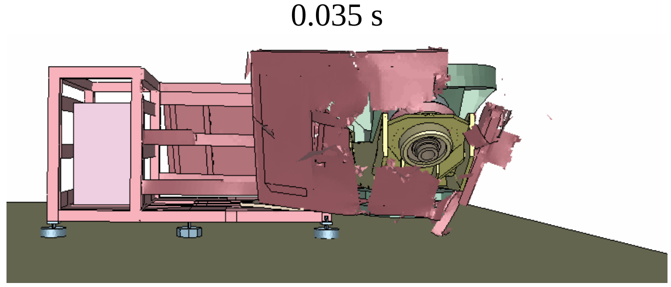
0.025 s



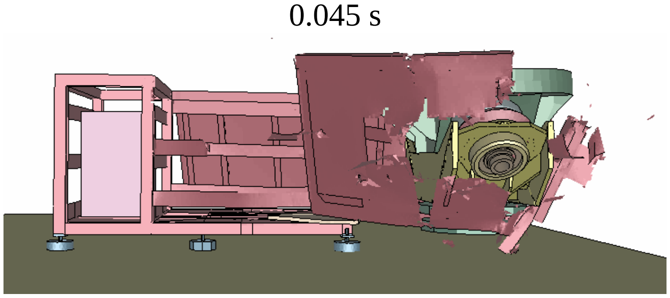
0.035 s



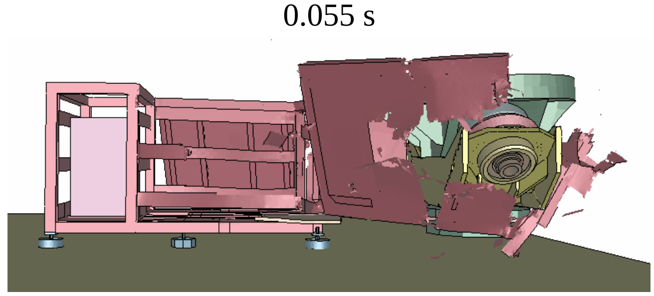
0.045 s



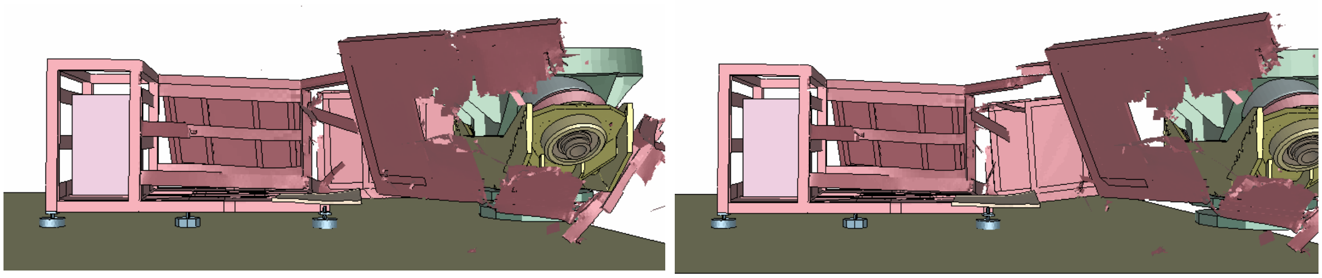
0.055 s



0.065 s

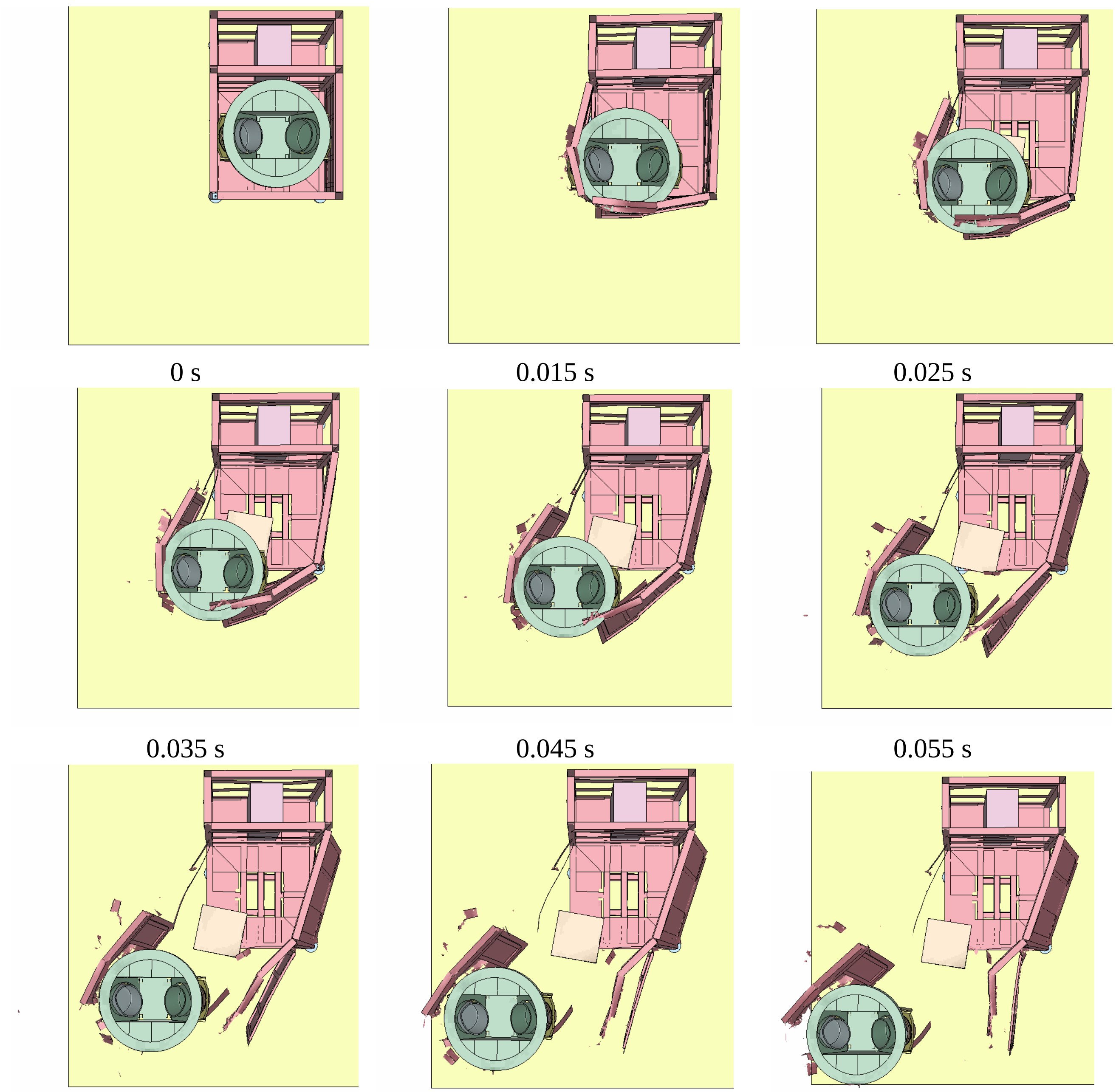


0.075 s



0.085 s 0.1 s

Figure 12.



0 s 0.015 s 0.025 s

0.035 s 0.045 s 0.055 s

0.065 s 0.075 s 0.085 s

Figure 13.

In Figure 15 the plots of total velocity in the points 1 (casing), 2 (mixer) (see Figure 14 are presented. The analysis of the plots shows that velocity of the rushed-out mixer decreases from 25 m/s to 20 m/s, while the case gets maximal velocity equal to 6 m/s. The analysis results showed that variation of the rushing-out angle and friction coefficient doesn't affect dramatically the decrease of mixer speed after penetration through the casing. This fact makes it possible to conclude that in the case of emergency (mixer rush-out) the covering case performs no serious protection for the personnel surrounding the construction.

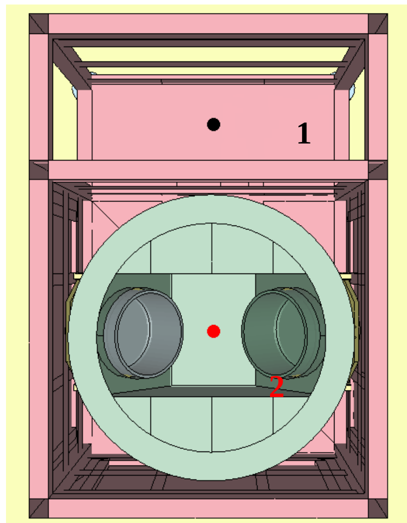


Figure 14.

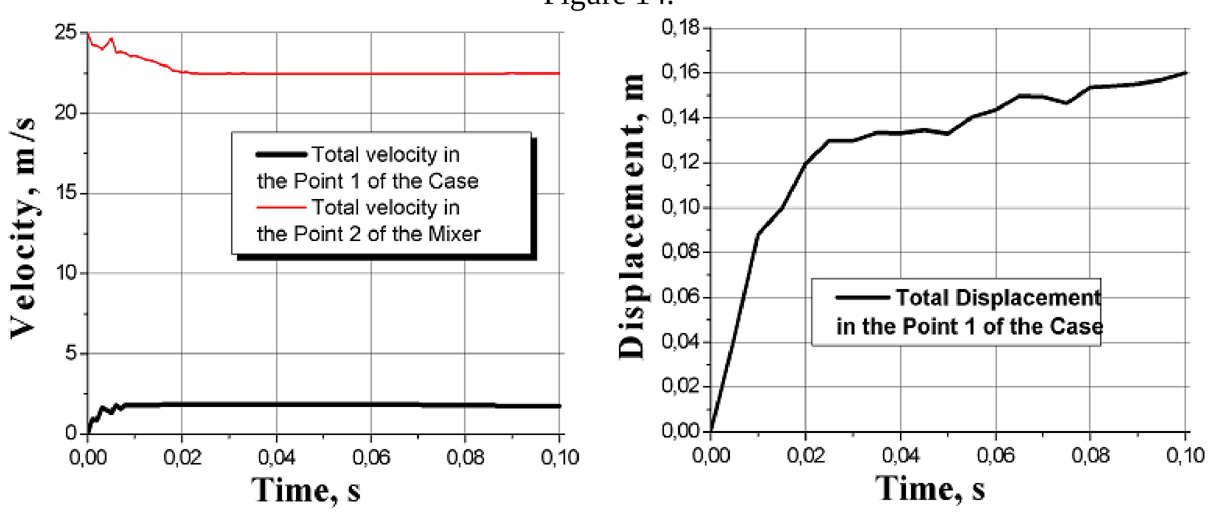


Figure 15.

Conclusions

In the current article the non-linear mechanical problems of the energy-saving high-speed planetary-motion mixer UM-500 are analyzed. The first part of the paper is devoted to stability analysis of the mixer. Motion stability loss effects are demonstrated for simple mathematical models.

The simulation of emergency situation is performed. Process of mixer departure out of casing is simulated with use of LS-DYNA. The analysis of the results obtained makes it possible to conclude that in the case of emergency (mixer rush-out) the covering case performs no protection for the personnel surrounding the construction. The case lowers the velocity of the flying-out mixer only for 5 m/s.

References

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