Simulation of pneumatic lifting of heavy structures

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Abstract

The purpose of this paper is to determine the value of the initial force which allows the rotation of a heavy metal part by an air bag around a fixed axis. This force depends on, among other things, the structure mass, air pressure in the airbag and contact interface between the metal part and the air bag. The initial folded state of the air bag do not permit to provide the volume to pressure relationship by a simple mathematical equation. Therefore finite element code LS-DYNA based on explicit time integration is used for simulation of a simple structure model consisted of three deformable walls and an inflatable air bag. The values obtained from analytical calculations for selected time are compared with the numerical results.

Keywords: finite element methods, large deformation, multibody dynamics

1. Introduction

The air bags, as their unmatched performance, rapid and easy deployment, are useful devices to lift heavy structures . Although the coated reinforced rubber material of pneumatic lifting system minimizes the risk of mechanical damage, sometimes metal protection is needed. Some of the inflatable air bags are offered to carry a heavy metal part of the device. This phenomena is used to construct an additional device which helps to increase mass that allows to keep buoyancy of a vehicle [4]. In the passive state folded elastic air cushions are stored in the metal container. Before the water crossing, the air cushions are filled with gas and additional buoyant force is generated. During this operation, the container changes its shape and metal parts are moved in respect to each others.

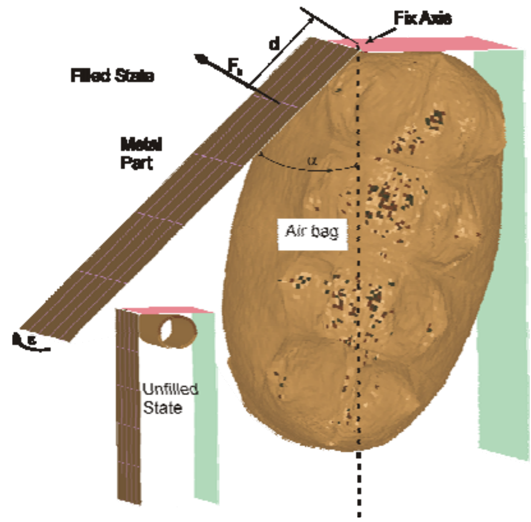

Figure 1: A model of the simple structure for two states: unfilled and filled

The problem of determination the value of the initial force which allows the rotation of the heavy metal part by the air bag filled with air is considered (Figure 1). Both FEM simulation and analytical calculation are employed to solve the problem.

2. Problem description

Suppose that a heavy metal part and an air bag constitute a system. The general form of the momentum equation with external forces for this system is [1]

$$\sum \mathbf{F}_{ext} + \int_{C.V.} \mathbf{g}\,\rho\, dV - \int_{C.V.} \mathbf{P}\cdot d\mathbf{A} + \int_{C.V.} \tau\cdot d\mathbf{A} = \frac{t}{dt}\int_{C.V.} \rho\,\mathbf{U}\, dV + $$

$$+ \int_{C.V.} \rho\,\mathbf{U}\,\mathbf{U}_{\mathbf{rn}}\, dV \qquad (1)$$

where $\mathbf{F}_{ext}$ is the force associated with the heavy metal part, $\int_{C.V.} \mathbf{g}\rho\, dV$ is total gravity force, $\mathbf{P}$ is surface force perpendicular to the surface (pressure), $d\,\mathbf{A}$ is the elemental surface area, $\boldsymbol{\tau}$ is shear stress, $\mathbf{U}$ is velocity of the air bag boundary, $\mathbf{U}_{rn}$ is the relative velocity component perpendicular to the surface, ρ is density and C.V. is control volume.

When control volume is both moving and deforming the main complication appears: the first integral on the right side of equation (1) must be taken outside volume.

On other side, if no force acts normal to a tensioned air bag surface, the surface must be flat. But if only pressure on one side of the surface differs from pressure on the other side, the pressure difference times surface area results in a normal force. For a very small area, when all forces are balanced, this resulting normal force depends on pressure and radii of the surface curvature. Therefore air bag surface which contacts with a metal part is not flat, but a quadric surface. This fact caused the problem with accurate determination the area of a contact surface an between air bag a metal part and force acts on the heavy metal part. A reverse problem was formulated: what value of the force F_k perpendicular to the surface of the heavy metal part is needed to move it from its initial position?

The main aim of the paper is to find simple relationship between the mass of the heavy metal part and driven force F_k caused by an air-filled airbag. It allows to assess the minimum value of the driven force necessary to move the heavy metal part around the fix axis. Therefore dynamics of the gas in the airbag before this moment is not important.

Due to the structure symmetry, the counterweight pivots of the heavy metal part around the fixed axle can be considered as

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two dimensional rigid body dynamic problem. The heavy metal part BC subjected to forces caused by pressure inside the air bag is shown in Figure 2.

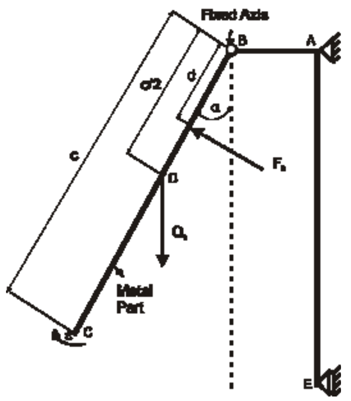

Figure 2: A two dimensional mechanical model of the structure

The general moment equation for rotation of a heavy metal part BC around point B is:

$$\mathrm{I_B}\,\varepsilon = \mathrm{F_k} \cdot \mathrm{d} - \mathrm{Q_k} \cdot \frac{\mathrm{c}}{2} \cdot \sin\alpha \tag{2}$$

where:

$$\varepsilon = \frac{d^2\alpha}{dt^2} = \ddot{\alpha} \tag{3}$$

is the angular acceleration of the centre of mass in the x-direction, with respect to fixed point B, attached to AB part of the system. α is the angle the BC part makes with the vertical line. F_k is the driven force caused by an air-filled airbag, d is the distance from D to fixed point B, c is height of the heavy metal part. In the initial consideration, it is assumed that a motion restraints of the revolute joint B are negligible.

The rotational inertia of the rigid body around an axis passing through fixed point B become

$$\mathrm{I_B} = \frac{\mathrm{m_k} \cdot \mathrm{c}^2}{3} \tag{4}$$

The weight Q_k of the heavy metal part is depended on its mass m_k and g is the acceleration due to gravity.

$$\mathrm{Q_k} = \mathrm{m_k} \cdot \mathrm{g} \tag{5}$$

The angular acceleration of the centre of mass of the heavy metal part can be expressed as follows:

$$\varepsilon = \frac{3F_k d}{m_k c^2} - \frac{3Q_k \sin\alpha}{2m_k c} = \frac{3F_k d}{m_k c^2} - \frac{3g}{2c}\sin\alpha \tag{6}$$

Combining the two equations (3) and (6) results in the second order differential equation

$$\ddot{\alpha} + \frac{3g}{2c}\sin\alpha = \frac{3F_k d}{m_k c^2} \tag{7}$$

A solution of the nonhomogeneous linear second order differential equation (7) can be obtained by a numerical method. Until, the object of interest is the minimum force F_k, the assumption $\sin\alpha \cong \alpha$ is true. Therefore, the general solution to the equation (7) is given by

$$\alpha = -\frac{B}{A^2}\cos(At) + \frac{B}{A^2} \tag{8}$$

where

$$A^2 = \frac{3g}{2c} \tag{9}$$

and

$$B = \frac{3d}{c^2}\frac{F_k}{m_k}\;. \tag{10}$$

The heavy metal part is the a square with the sides which have invariable length c. The moment of force F_k needed to extort the motion of the rigid part is describing as follows:

$$F_k = \frac{\alpha\, c\, g\, m_k}{2d\left\{1 - \cos\left[\left(\frac{3g}{2c}\right)^{0.5} t\right]\right\}} \tag{11}$$

where t is the time.

It means that force F_k is a linear function of heavy metal part mass and an inverse function of the distance from D to fixed point B - d. The trigonometric function of time in the denominator noticed that force F_k is a periodic function. If

$$H = \frac{\alpha}{d}\frac{m_k}{F_k}\;. \tag{12}$$

the equation (8) takes the form

$$H = \frac{2}{cg}\left[1 - \cos\left(\sqrt{\frac{3g}{2c}}\,t\right)\right] \tag{13}$$

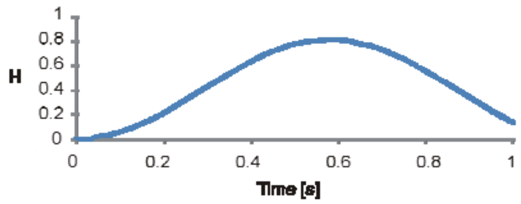

Figure 3: Change of term H in respect to time

The above consideration was done with assumption that $\sin\alpha \cong \alpha$. To obtain a full solution, a numerical method is used in the form of numerical simulation.

3. FEM simulation

The FEM simulation of the simple structure model consisted of three deformable walls and an inflatable air bag (Figure 1) is performed. The LS-Dyna code based on explicit time integration is used. Two fixed perpendicular walls are made of steel. The air bag is attached to the horizontal wall with an extra nodes set. One vertical wall is fully supported. The other vertical wall there is a moving part made of light metal or of composite material corresponding to it with strength and stiffness, for example composite sandwich (Figure 1). The revolute joint is placed between the horizontal wall and the other vertical wall. Its rotation is assured by the filled air bag. Extending volume of air bag presses on moving metal part causing its rotation.

The layered orthotropic composite material model for an air bag elements is assumed [2]. The laminated shell theory is activated to model properly the transverse shear deformation of material. At the beginning, the air bag is folded therefore it does not act on any walls of the structure.

Due to computational efficiency, the Belytschko-Lin-Tsay shell elements are used to create a model. These elements are based on a combined co-rotational and velocity-strain formulation.

LS-Dyna used a control volume algorithm in order to simulate air bag inflation. Since the airbag model is employed to simulate air cushion behaviour, a curve describing the input mass flow rate has to be determined and declared in the model. For constant mass inflow, the air bag is filled during 0.5 s. The proposed curve is depicted in Figure 4.

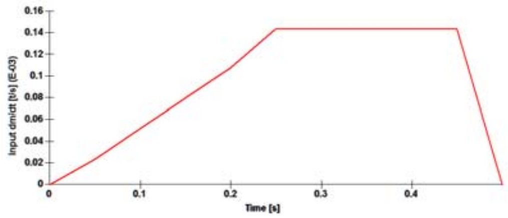

Figure 4: The input mass flow rate curve for the simple airbag model

The position, orientation and current surface area of the air bag elements are computed and stored at each time step. The pressure in the air bag corresponding to the control volume is determined from Gamma Law Gas Equation of State [3].

The nodes to the surface type of contact is applied to describe an interaction between the air cushion and other components of the device.

Simulations for two values of heavy metal part mass were performed. The mass was reduced by about 6.8% in one of them.

4. Results and Conclusions

A study is conducted to investigate the minimum value of the initial force which is needed to move the heavy metal part by the inflatable air bag.

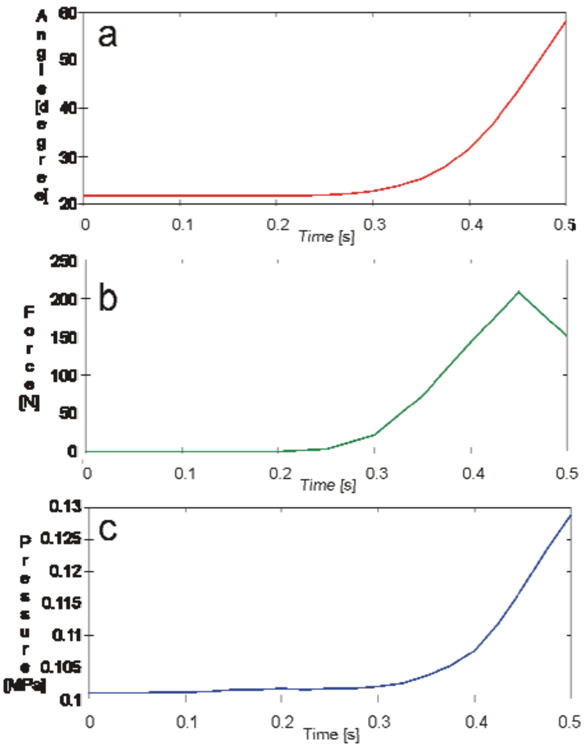

Figure 5: Changes of: a) the rotation angle, b) the value of force F_k, c) pressure vs. time

Therefore a simple method is needed to assess a sought value and determine the permissible mass of the moving part of the device. FEM simulation is performed to analyse the elements with great stiffness difference between the extensive, deformable air bag and the metal part. However, the results validation is necessary.

Three diagrams are presented: change of the rotation angle (Figure 5a) which is caused by force F_k (Figure 5b) coming from pressure inside the air bag (Figure 5c). The value of the rotation angle (Figure 5a) increases according to the change of the force value F_k (Figure 5b).

A 10% difference in value of initial force is noticed during comparison of results of the analytical calculations for the time when the metal part begins the rotation with the results of numerical analyses. This difference can be caused by an unsuitable material model.

The change of the force value for two values of the heavy metal part mass in respect of time is shown in Figure 6.

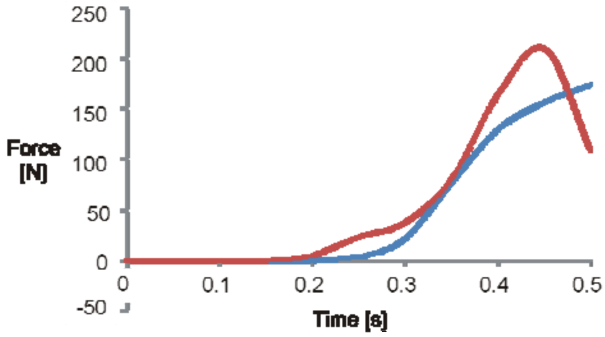

Figure 6: Changes of force F_k value vs. time

Two main conclusions can be written:

- Any value of the initial force F_k allows the rotation of the heavy metal part;
- It is impossible to rotate the heavy metal part by angle 90° with the use of one air bag with an assumed shape.

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References

[1] Bar-Meir G., *Basis of Fluid Mechanics*, www.potto.org, 08.12.2010.

[2] *LS-DYNA Keyword User's Manual*, ver. 971/Release4 Beta, vol. 2, pp. 189-166, 2009.

[3] *LS-DYNA Theory Manual*, compiled by J. O. Hallquist, 2006.

[4] Patent Application P.392851.