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ARKADIUSZ CZARNUCH*, EDWARD LISOWSKI**

STUDIES OF TRUCK SEMITRAILER STABILITY DURING LOADING AND UNLOADING

BADANIA STATECZNOŚCI NACZEPY SAMOCHODU CIĘŻAROWEGO PODCZAS ZAŁADUNKU I ROZŁADUNKU

A b s t r a c t

The paper presents the effect of air suspension system on semi-trailers during loading and unloading processes while using a forklift. The mathematical model was created, which takes into account a sharp loading on the rear platform of a semi-trailer. The entry of a loaded forklift onto the rear platform of a semi-trailer causes rapid lowering of the platform, which contributes to an unstable movement of the forklift.

Keywords: *air suspension, semi-trailer*

S t r e s z c z e n i e

W artykule przedstawiono symulację działania pneumatycznego układu zawieszenia naczepy samochodu ciężarowego podczas załadunku i wyładunku przy wykorzystaniu wózka widłowego. Zbudowano model matematyczny dla przypadku nagłego obciążenia tylnej części naczepy to jest przy wjeździe obciążonego wózka na naczepę i badano zachowanie się układu. Wjazd obciążonego wózka na naczepę powoduje skokowe obniżenie platformy, co ma niekorzystny wpływ na stabilność jazdy wózka.

Słowa kluczowe: *układ pneumatycznego zawieszenia, naczepa*

* MSc. Arkadiusz Czarnuch, Wielton S.A.
** Prof. PhD. Eng. Edward Lisowski, Institute of Applied Informatics, Mechanical Faculty, Cracow University of Technology.

Nomenclature

p_S – pressure of pneumatic piston [Pa]
p_j – unitary pressure per strength [Pa/N]
p_Z – pressure in air tank [Pa]
F_S – force on airbag [N]
F_W – force on hanger bracket [N]
A_E – spring effective area [m^2]
k – air spring stiffness [N/m]
C – damping coefficient [Ns/m]
C_C – critical damping coefficient [Ns/m]
ζ – damping ratio
m – mass [kg]
m_{nr} – unsprung mass [kg]
V – volume [m^3]
V_S – volume of airbag [m3]
κ – adiabatic coefficient
ρ – density [kg/m^3]
x – displacement [m]
x_s – height of airbag working area [m]
υ_Z – velocity of air flow [m/s]
h_{tarcia} – fraction loss [m]
h_{lok} – local loss [m]
d – diameter of pipes [m]

1. Introduction

The suspension is one of the basic systems in vehicles which is responsible for safety and comfort. It is the system which connects the vehicle structure to wheels and allows for relative motion between them [1, 2, 4]. Reaction forces from the wheels are compensated and transferred to the structure of the vehicle.

There are a few types of suspension: mechanical, hydraulic and pneumatic. In pneumatic suspensions the air is a working medium. The air is characterized by low bulk elastic modulus K_s = 0.14 GPa, which means that it changes its volume under a small variation of pressure. It is an advantage for air suspensions, but in some cases it may be a disadvantage, especially while rapid loading and unloading, where large changes of force occur resulting in height movement in airbag, which consequently influences the vehicle stability. The article deals with the reaction forces appearing in suspension during loading of a semi trailer with a forklift from loading docks. Nowadays pneumatic suspension is equipped with an automatic levelling system but that system is not able to compensate rapid and abrupt load which occurs during loading with a forklift from a loading dock.

2. Statics analysis of semi-trailer platform

To analyze the statics we present a typical case of loading and unloading of a semi trailer. The forklift with cargo drives onto the rear semi trailer platform from a loading dock. It is assumed that the semi trailer platform is being levelled by the pneumatic system to the level of the loading ramp. Force distribution on semi trailer while loading is shown in Fig. 1. During driving onto the platform by the first axle of the forklift, the semi trailer is subjected to gravity forces and the rear part of platform is subjected to force F coming from the first axle of the forklift. Reaction forces are R_1 and R_2. Initially we present a simple 2D beam system supported in two points, front part as a fifth wheel of a tractor and the rear part as an assembly of suspension.

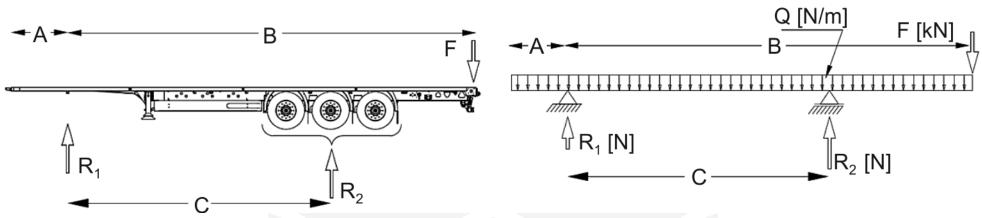

Fig. 1. Chassis of the trailer during loading and unloading

Rys. 1. Schemat podwozia naczepy siodłowej przy wjeździe wózka na platformę

3. Suspension schema

The suspension schema for one wheel is shown in Fig. 2. The system contains air spring 4, damper 3 and hanger bracket 1. In the system the characteristic values describing the suspension are: stiffness coefficient *k* which describes the air spring and damping coefficient *C* describing the damper.

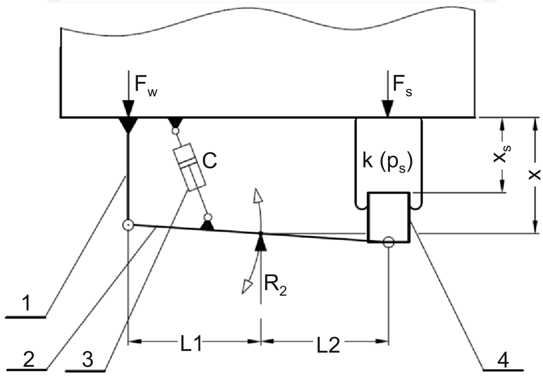

Fig. 2. Suspension model

Rys. 2. Model zawieszenia

Reaction R_2, is partially transferred to the semi trailer chassis by hanger bracket 1, force F_W, and by pneumatic air spring 4, force F_S. The kinematics and characteristic values for the suspension were determined based on the data provided by suspension and axle manufacturer SAF [3]. The X dimension describes the distance between the wheel center and the bottom of the chassis, and X_S is the height of the working area of the air spring. Relation between these values is described by the equation (1):

$$\Delta X_S = \frac{L_1}{L_1 + L_2} \cdot \Delta X \tag{1}$$

The pneumatic airbag SAF 2619V [3] was considered. The unitary pressure per 1 N of loading for airbag is:

$$p_J = 22.7 \text{ Pa/N} \tag{2}$$

Basing on the unitary pressure (2) the effective area A_E (3) was determined

$$A_E = \frac{1}{p_J} = \frac{F_S}{p_S} \tag{3}$$

The volume V_0 in the air spring relating to the initial conditions was determined based on the effective area A_E corrected by additional volume in neutral space.

$$V_O = A_E \cdot x_{SO} + \left(\left(\frac{\pi \cdot D_Z^2}{4} - A_E \right) \cdot x_{SO} \right) \tag{4}$$

where:

x_{SO} – the height of working area in the air spring related to the initial conditions.

The initial pressure in the air spring P_{S0} was determined basing on the initial volume V_0 and the initial impact force on air spring F_{S0} coming from the weight of the semi-trailer:

$$p_{S0} = \frac{F_{S0}}{A_E} \tag{5}$$

Force F_S was determined by suspension kinematics and reaction R_2 coming from the contact of the wheel with the ground:

$$F_S = \frac{L}{L + L_1} \cdot (R_2 - m_{NR}) \tag{6}$$

where:

m_{NR} – unsprung mass including tires, wheels, suspension and axle.

Force F_S was the base for the determination of the correlation between pressure in the airbag and loading of axle R_2, the correlation is described by equation (7). The pressure is designated for two airbags working on one axle. This correlation corresponds to the constant volume of the airbag and constant height from the axle to the chassis bottom:

$$p_S(R_2) = \frac{L}{2 \cdot (L + L_1)} \cdot (R_2 - m_{NR}) \cdot p_J \tag{7}$$

In the case where automatic levelling system is switched off and during manual handling, the pressure in the airbag corresponds to actual loading and during the change of loading the volume in the airbag changes. That transformation was treated as adiabatic process where $p_S \cdot V^{\kappa}$ = const, the initial pressure and volume, P_{S0} and V_0, correspond to study state conditions.

$$P_S = P_{S0} \cdot \left(\frac{V_0}{V_1} \right)^K \tag{8}$$

The movement of axle in relation to the chassis was described by differential equation of motion (9):

$$m \cdot \frac{d^2 x}{dt^2} + c \cdot \frac{dx}{dt} + k(p, V, x) \cdot x = F_S(t) \tag{9}$$

where:

$k(p, x) \cdot x$ – spring force of airbag,

$F_S(t)$ – force on airbag.

Value k describes the spring characteristic of the airbag and it is an increment of the force to the change of the airbag height:

$$k = \frac{dF_S}{dx} \tag{10}$$

According to (5), the stiffness coefficient k may depend upon the pressure in airbag [1]:

$$k = A_E \cdot \frac{dP_S}{dx} \tag{11}$$

These values were determined for the system where automatic leveling valve was switched off, the system was closed. The initial pressure in the airbag corresponds to unloaded semi trailer. In this case, during loading the pressure changes in airbag due to volume change, equation (8). This occurs when the platform level of a semi trailer is positioned manually to the dock level, then automatic leveling valve is switched off. The differential equation of motion (9) for the suspension system is as follows:

$$\frac{d^2 x}{dt^2} = -\frac{C}{m} \cdot \frac{dx}{dt} - \frac{1}{m} \cdot \left(A_E \cdot \frac{dp_S}{dx} \right) \cdot x + \frac{1}{m} F_S(t) \tag{12}$$

The damping level C was determined using the damping ratio $\varsigma = 0.8$, which describes the relation between damping coefficient C and critical damping coefficient C_C [2]:

$$\varsigma = \frac{C}{C_C} \tag{13}$$

The critical damping coefficient is defined (14):

$$C_C = 2 \cdot \sqrt{k \cdot m} \tag{14}$$

To analyze the suspension system, where self-leveling valve is working during loading, a module which controls the movement was added to the mathematical model. The self-leveling system works by controlling the distance between wheel center and chassis and appropriately to motion, suitable amount of air is added to or subtracted from the airbag.

It was assumed that the system is powered from an air tank, where there is constant pressure p_z. The air tank is connected with the airbags by elastic pipes of constant length and diameter. In the system there are two additional pneumatic spool valves.

In order to designate the amount of air that can be provided to the airbag, flow velocity from the air tank υ_Z was calculated by the Bernoulli's equation. The local and linear losses were taken into consideration.

$$\upsilon_Z = \sqrt{\frac{2 \cdot (p_Z - p_S)}{\rho} - 2 \cdot g \cdot (h_{\text{tarcia}} + h_{\text{lok}})} \tag{15}$$

Based on the flow velocity the volume flow rate was determined.

$$\dot{V}_1 = \upsilon_Z \cdot \frac{\pi \cdot d^2}{4} \tag{16}$$

To increase the stiffness coefficient of air spring, mathematically it was performed by increasing the pressure p_p per unit of time, according to adiabatic process:

$$\frac{dp_p}{dt} = p_S \cdot \left(\frac{V_1}{V_S}\right)^{\kappa} dt \tag{17}$$

4. Results

To solve the differential equation of motion (12) the Math-Lab/Simulink software was used. The initial conditions for the equation were assumed as for an unloaded semi trailer. Additional loading from the first axle of the forklift was simulated by rectangular function $R_2(t)$. The obtained displacement $X(t)$ was used to determine the temporary volume of the airbag. The pressure in the airbag was defined on the basis of the adiabatic transformation and used to determine the stiffness coefficient of the air spring. Obtained stiffness coefficients were passed to the next iteration of motion equation.

The results of the simulation are shown in Fig. 3–5. The results include the system without and with self-leveling line 1 and 2, respectively. Fig. 3 shows the motion of wheel center in time. Adequately to the change of the position the pressure and volume of the airbag is changed, as shown in Fig. 4 and 5.

Presented graphs show the system response to the rapid and abrupt load. In period 0–1 s the system is in steady state conditions, the pressure and initial volume correspond to unloaded semi-trailer including the vehicle's weight. The displacement of axle in relation to the chassis is zero. After 1 s, additional force was added to the motion equation causing the 80 mm displacement of the system.

The behavior of the system at the initial stage with and without self-leveling, after additional force is similar, in both cases the level of displacement is the same. In case 1 the respond signal of displacement changes to the level –90 mm and after 0.5 s it stabilizes to level –80 mm. In case 2 with self-leveling system signal changes also to the –90 mm but it stabilizes after 4.5 s to the initial level.

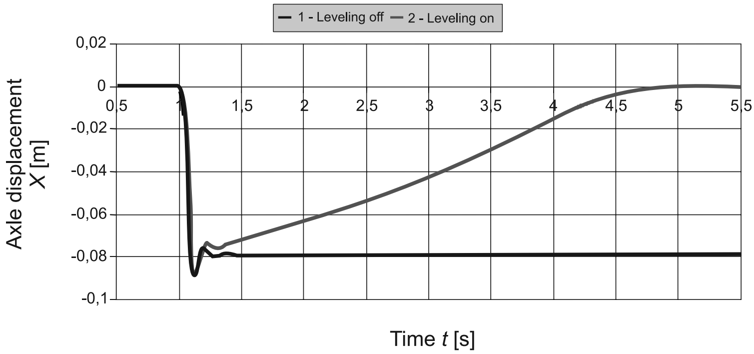

Fig. 3. Movement of axle in time

Rys. 3. Przemieszczenie osi zawieszenia w czasie

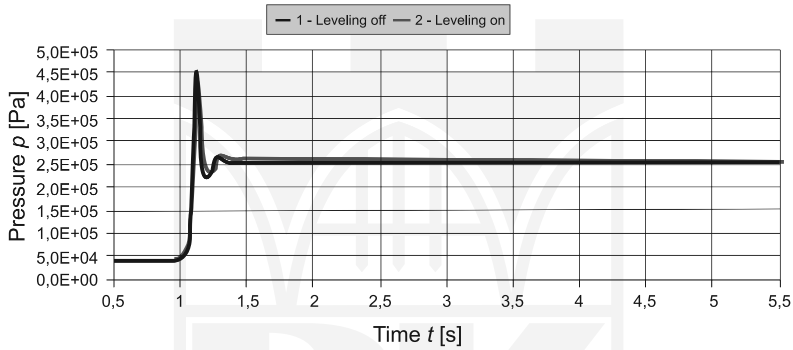

Fig. 4. Pressure in piston chamber in time

Rys. 4. Zmiana ciśnienia w siłowniku w czasie

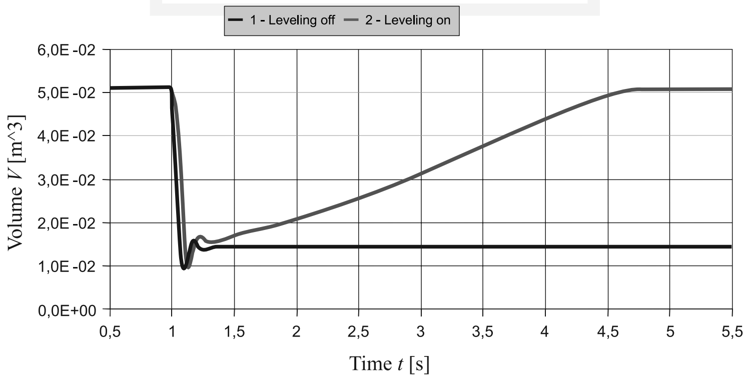

Fig. 5. Volume of piston chamber in time

Rys. 5. Zmiana objętości komory siłownika w czasie

The pressure graphs show rapid change from 0.05 MPa to 0.45 MPa in a short time of 0,15 s. The reason of this rapid change is the big difference between the initial load and the added load which increased 3,5 times. The signal stabilizes after 0,3 s and it is similar for both considered cases with and without self-levelling.

Similarly to displacement the volume signal changes. In short time, 0.3 s, volume decreases to the neutral level of 0.014 m^3. In case 2 with self-levelling, when the initial level changes, then additional amount of medium is added. The volume of airbag is changed under a constant pressure. It should be noted that the levelling system is activated following the change in displacement of 1 mm, and as a result that volume increases in the first phase.

5. Conclusions

This paper presents a theoretical simulation of air suspension behavior in the case of sudden load changes. The simulation confirms, that the air suspension is not able to compensate sudden and large load change.

The self-levelling system stabilizes displacement of the air suspension to the initial value, but it does not contribute to the reduction of displacement. The time necessary to return to the initial position is relatively long, which has an adverse effect on the stability of the semi trailer during loading and unloading.

Developed simulation of air suspension can be used for detailed analysis of the impact of different factors on the system work. The following factors mainly contribute to the unstable air suspension working during large load changes: low bulk elastic properties of air, the initial pressure is adjusted to the current load, large capacity of airbags in relation to the supply system, the neutral volume in airbag, where increased pressure does not generate vertical force on a piston, the self-levelling system does not contribute to the reduction of the displacement level.

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