SIMULATION TESTS OF THE BRAKING PROCESS OF AN AGRICULTURAL TRACTOR

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Abstract: The agricultural industry is growing very quickly. Large areas of fields make tractors work at higher speeds, with which they also move on public roads. Except acceleration, the agricultural tractor must also be stopped. There are emergency situations on the roads that require sudden braking, and therefore a quick stop of the vehicle. Drum brakes are used in most farm tractors. They contain a friction pair (shoes and drum) which as a result of cooperation changes the kinetic energy of the motion into thermal energy. Unfortunately, this creates a huge amount of this energy. This can cause overheating of the friction lining, which can lead to permanent damage. This paper presents the results of simulation tests of the braking process during single emergency braking. It has been shown that in some situations the temperature can reach a higher value than that which is safe for friction material components.

Keywords: BRAKES, AGRICULTURAL TRACTOR, FRICTION, HEATING PROCESS, COOLING PROCESS

1. Introduction

Agricultural tractors have been a must for every farm for many years. They are used mostly in agricultural works, but not only. The specificity of agricultural production means that the acreage of processed fields is increasing. Therefore, the number of kilometers covered increases naturally. Farmers, in addition to cultivation and harvesting, must deliver their crops to collection points. These are usually several or even over a dozen kilometers away. Tractors are also used to overcome them. In combination with trailers, they are a sufficient means of transport [1].

The specificity of today’s times which results in a dizzying pace of life means that no one can afford to waste time. This situation is being met by producers of agricultural equipment who are offering bigger, stronger and faster tractors. Constructions sold today easily reach speeds of 50km / h together with a loaded trailer (or even several) [2].

However, accelerating such a large mass (reaching several dozen tons) is not an easy task. The real challenge is quick and efficient braking. On public roads there are often emergency situations in which a sudden loss of speed is required [3, 4]. In the event of a breakdown, there is a real danger to the health or even life of road users. It is therefore important that the components of the braking system work quickly and reliably throughout the entire service life [5].

Drum-type friction brakes are used in most agricultural tractors [6]. The braking process consists in pressing the linings against the drum rotating together with the wheel. The resulting friction effect changes the kinetic energy of a moving tractor into thermal energy. It is then returned to the environment due to convection, conduction and radiation. However, it is not always possible to dissipate heat energy quickly enough. In the case of a sudden braking, it happens that the temperature of the friction elements reaches up to several hundred degrees. For some materials, this means a loss of stability and the formation of so-called fade phenomena [7, 8]. It involves sublimation of the matrix of the friction material, which creates a gas cushion between the friction couple. This is associated with a loss of braking capability. This work is aimed at checking whether there is a risk of fading during emergency braking in modern, fast agricultural tractors.

2. Mathematical model of braking process

The force of the braking process may be described as a negative derivative of the vehicle’s kinetic energy [8]:

\[ P = \frac{d}{dt} \left( \frac{m v^2}{2} \right) \]

(1)

or

\[ P = -m R^2 \omega(t) \alpha \]

(2)

where: \( m \) - vehicle’s mass, \( v \) - speed of the vehicle, \( R \) - dynamic radius of the road wheel, \( \alpha \) - angular velocity of the wheel, \( t \) - time, \( \alpha \) - angular deceleration. Assuming that the braking deceleration is constant, we may say that:

\[ \omega(t) = \omega_0 + \alpha t \]

(3)

A simple stability analysis of the vehicle made demonstrated that approximately 60% of the total braking force comes from the front wheels (roughly 15% per each of the four brake shoes on the front axis) [1]. It has been assumed that each of the brake pads generates identical braking force. The relation between the braking force of one wheel and the complete vehicle is as follows:

\[ F_b = \frac{100\% \cdot F_{b0}}{2 \cdot 15\%} \approx 3.33 \cdot F_{b0} \]

(4)

where: \( F_b \) - braking force generated by one front wheel, \( F_{b0} \) - total braking force of the vehicle. On that basis, the braking force of the vehicle may be described as [9]:

\[ P = -3.33 \iint f_b \cdot dA \cdot v_d \]

(5)

where: \( f_b \) - frictional force per surface unit, \( v_d \) = \( \omega(t) \cdot r \) - brake drum linear speed at radius \( r \), \( A \) - disc and shoe contact surface area (in our case \( A = 0.01 m^2 \)). The braking force is also expressed as the relation [9]:

\[ P = f_b(t) \cdot \omega(t) \iint r_m \cdot dA \]

(6)

where: \( r_m \) - distance from the shoe’s centre to the disc rotation axis (in our case \( r_m = r \) ). Comparison of the two equations makes it possible to determine the \( f_b \) coefficient:

\[ f_b = -\frac{m R^2 \omega}{3.33 r_m A} \]

(7)

Assuming that the vehicle’s deceleration occurs only through the action of the brake disc and pad, the heat flux may be designated using the equation [10]:

\[ q(r, t) = -f_b \cdot v_d(r, t) \]

(8)

or by substituting:

\[ q(r, t) = \frac{m R^2 \omega}{3.33 r_m A} (\omega_0 + \alpha t) \]

(9)

Amontons - Coulomb friction law [11] makes it possible to determine the contact pressure, which in the analyzed case is as follows:

\[ p = \frac{P}{\mu v} \]

(10)

where: \( \mu \) - coefficient of friction between the disc and pad. Also, the study takes into account the heat exchange occurring between the disc and pad, expressed as the following relation [12]:
The necessary material data, i.e. density, thermal conductivity and thermal capacity of the friction pair were determined experimentally. A summary of the above data is shown in Table 2.

Comsol Multiphysics 4.4 software was used for simulation tests. The developed model has been simplified relative to the real parts of the tractor. The simplification concerned geometry (shapes and fragments that did not have a significant impact on the heating process were removed) and it was aimed at avoiding unnecessary compaction of the mesh. Ultimately, the grid consisted of nearly 6,000 elements, which gave over 27,000 degrees of freedom. The study step was 0.05s. The temperature was measured at the central contact point at a depth of 0.2 mm both in the drum and in the lining. Temperature profiles are shown in figure 2 (lining temperature) and figure 3 (drum temperature).

During the tests it was assumed that: braking takes place without slip, the tire adhesion coefficient to the ground is 1.0 (this leads to a traffic delay of $9.81 \text{ m/s}^2$), the ambient air temperature is $25^\circ C$, the invariability of the friction coefficient of the linings against the drum (in fact it changes with temperature), contact pressure that is constant and even for both linings, uniformity of the material and contact with the entire surface, no influence of external factors (e.g. unevenness of the road, air resistance, operation of the vehicle suspension). The initial speed of the vehicle was set at 50km/h.

### 4. Results and discussion

In the research, the first 10 seconds counted from the start of braking was analyzed. The study step was 0.05s. The temperature was measured at the central contact point at a depth of 0.2 mm both in the drum and in the lining. Temperature profiles are shown in figure 2 (lining temperature) and figure 3 (drum temperature).

### 3. Object and methodology of research

The object of research was CAD models of the braking system parts (Fig. 1) from a popular agricultural tractor in Europe (linings and drum). The most important technical specifications of the tractor are summarized in table 1.

The developed model has been simplified relative to the real parts of the tractor. The simplification concerned geometry (shapes and fragments that did not have a significant impact on the heating process were removed) and it was aimed at avoiding unnecessary compaction of the mesh. Ultimately, the grid consisted of nearly 6,000 elements, which gave over 27,000 degrees of freedom. Comsol Multiphysics 4.4 software was used for simulation tests. The necessary material data, i.e. density, thermal conductivity and thermal capacity of the friction pair were determined experimentally. A summary of the above data is shown in Table 2. In addition, the friction coefficient of friction, which is 0.36, was determined.

### Table 1: Mechanical properties of selected powder materials

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheelbase</td>
<td>c</td>
<td>2925mm</td>
</tr>
<tr>
<td>Rear axle width</td>
<td>b</td>
<td>2602mm</td>
</tr>
<tr>
<td>Center of gravity distance from the front axle</td>
<td>c1</td>
<td>1345mm</td>
</tr>
<tr>
<td>Center of gravity distance from the rear center of the left tire</td>
<td>b1</td>
<td>1301mm</td>
</tr>
<tr>
<td>Height of the center of gravity</td>
<td>h</td>
<td>910mm</td>
</tr>
<tr>
<td>Total mass</td>
<td>m</td>
<td>16000kg</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>$V_{\text{max}}$</td>
<td>50km/h</td>
</tr>
<tr>
<td>Maximum slope angle</td>
<td>$\phi$</td>
<td>$20^\circ$</td>
</tr>
</tbody>
</table>

### Table 2: Technical data of friction materials

<table>
<thead>
<tr>
<th>Shoe lining</th>
<th>Thermal conductivity</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>140 [W/(m*K)]</td>
<td>2600 [kg/m$^3$]</td>
</tr>
</tbody>
</table>
successive charts: thermal energy produced in the braking process (fig. 4) and given to the nearest environment (fig. 5). Both lines have a "smooth" course, so it can be assumed that the simulation went correctly.

Analyzing the obtained data, it can be stated that 237.28kW was produced in one of the front wheels during braking, while just over 1.5kW was lost within 10 seconds of starting braking due to convection and radiation. This means that the cooling process is much slower than heating and the brakes remain "hot" for a long time after stopping. In the event that there would be a need for emergency braking in the near future, the risk of fade would increase significantly.

5. Summary and conclusions

This paper presents a mathematical model of the agricultural tractor braking process and simulation tests carried out on its basis. It was found that:

1. Emergency braking of an agricultural tractor with a total weight of 16000kg from a speed of 50km/h takes about 1.4s;
2. 237.28kW of thermal energy is generated as a result of friction generated in the brakes;
3. The brake lining heats up to 835.9K during 0.9s from the beginning of braking; after this time the temperature drops because the vehicle speed is already low, and the heating process is slower than cooling;
4. The drum heats up to 633.15K in 0.8s, followed by cooling for the same reason as in the linings;
5. Due to the fact that the friction material is a composite material whose matrix is usually a resin with a maximum allowable operating temperature of 500-800K [13, 14] there is a real risk of fade.

6. References