Research of resistance forces in the contact zone between the seal and the floor of a mobile robotic air cushion platform

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Abstract. Traditionally mobile robotic platforms are used in modern production facilities when performing transport operations, as well as in the process of assembling the finished product. With the increase in the load capacity of such platforms, the cost of their operation increases. But the use of an air cushion as a payload mass compensation system can increase their energy efficiency and reduce the cost of their operation. As a result, the scope of their possible application increases significantly. The article presents the main tasks that can be solved with the help of mobile robotic platforms on an air cushion in the complex automation of production. The use of an air cushion increases the energy efficiency of the transport system, which is a very urgent task. The design of the layout of such a platform is presented. The emphasis is placed on the importance of using a pressure seal, which allows achieving virtually zero clearance between it and the floor. A possible arrangement of such an air cushion sealing unit is shown. The computational model of this node built for finite element modeling in the ANSYS Workbench environment is presented. The main calculation cases that occur at various stages of the functioning of a mobile robotic air cushion platform are listed. The deformations of the seal for these cases are shown and the values of the normal force occurring in the contact zone of the seal and the floor for each of them are determined. The contact area of the seal and the floor in each case is also indicated. The dependences reflecting the change in the normal force of the simulation process with different coefficients of friction for the seal-floor pair are constructed. The behavior of the considered compaction unit of the mobile robotic platform in the process of its movement, depending on the direction of movement, is modeled.

1. Introduction

Complex automation of production is impossible without the use of automatic platforms. Such platforms are designed not only for moving parts between different production sites, but also for the assembly and installation of large-sized technological equipment, as well as the assembly of large and heavy products.

With the size and the weight of the products, which must be moved relatively each other with a high accuracy in the absence of traditional lifting equipment, the problem of smooth, without jerks caused by friction, movement of assembly elements is very relevant. A promising solution to this problem is the use of a variety of mobile robotic transport platforms [1, 2, 3]. Such a solution will
significantly simplify and in the future automate the work with large-sized products.

Often, heavy-duty platforms have another significant drawback associated with an increase in energy consumption, with an increase in their load capacity. There are also difficulties with maneuvering under heavy loads.

To solve the above problems, you can use a payload compensation system built on the basis of an air cushion. And by minimizing the gap between the seal and the floor plane, you can significantly increase the energy efficiency of the system as a whole.

2. Problem statement

Paper [4] describes the design of a mobile robotic platform for cargo transportation equipped with an air cushion (Figure 1).

Figure 1. Mobile robotic cargo transport platform equipped with an air cushion

A feature of the considered mobile transport system distinctive from traditional hovercraft vehicles is the absence of a gap between the seal and the floor. As shown in [4], the energy efficiency of such a transport system increases with a decrease in this gap and reaches the maximum possible value at its value equal to zero.

Indeed, with such a configuration of the system, air leaks from the air cushion are possible only through the micro-roughness of the floor. And given that the mobile transport system under consideration is operated in the conditions of storage facilities, it is possible to ensure the availability of high-quality floor covering. In this case, the size of the micro-roughness is small and the leakage losses can be neglected.

The scheme in which the air cushion seal is pressed against the floor has certain disadvantages. The main thing is that during the movement, there is friction between the seal and the floor and it will be the higher the stronger the seal is pressed against it. The pressure force of the seal increases with the pressure in the air cushion, which leads to an increase in sliding friction when moving.
For example, we consider a platform with a rectangular shape - 1x2 m, and a mass of 1000 kg. Along the perimeter of this platform there is a seal, which is a round pipe with a diameter of 100 mm and a wall thickness of 5 mm. The seal is made of Elastollan R1000 material. To press the seal to the floor, a distributed clamp is used (Figure 2), pivotally fixed around the perimeter of the platform.

3. Calculated cases
The paper simulates four situations that arise during the operation of the system.

The first model corresponds to the case in which the seal is pressed against the floor, while there is no pressure in the air cushion.

The second model corresponds to the case in which the seal, in addition to the forces pressing it to the floor, is affected by excessive pressure from the air cushion.

In the third model, in addition to the above forces, there is an additional pressure acting on the inner surface of the seal.

The fourth model is similar to the second, but after applying the above forces, a movement with a given speed in the horizontal direction is added.

4. Platform sealing model
For finite element modeling in the ANSYS Workbench environment, a calculation model is constructed, shown in Figure 3. Element 1 corresponds to a fixed platform wall, element 2 is a clamp and has the ability to rotate around the R point. Element 3 corresponds to the seal, and element 4 – to the support surface.

To reduce the computational resources for modeling, a fragment of the described system with a depth of 1 mm is considered. This simplification made it possible to reduce the solution time and use a finite element grid of the required quality (the size of one element is 1 mm).

Elastollan R1000 is used as the sealing material. The Mooney-Rivlin model with three coefficients is used for its modeling. Their values are determined both manually [5] and by means of ANSYS Workbench based on data on uniaxial tension of the material sample.

The contact of the seal with the platform wall and the clamp is modeled without taking into account the friction forces and with the floor surface. The value of the coefficient of friction forces of rest and sliding is assumed to be equal to 0.6 [5].

The pressure force of the seal is 600 N/m. The excess pressure to compensate for the weight of the load in 1000 kg with the specified parameters of the platform will be 4900 Pa.
The process of applying loads for all calculated cases is multi-stage. In the first stage, a clamping force is applied, and its value increases linearly from 0 to the nominal value throughout the entire stage. After that, pressure is applied in the same way. In the last calculated case, then the movement process begins.

5. Simulation of the seal contact by the finite element method

5.1 Calculated case 1

Despite the fact that this case (Figure 4) actually describes a static situation and as such there is no friction force, its value must be estimated and similar parameters will be compared with it in other calculated cases.

Figure 5 shows the plot of the strain distribution in the calculated model. The pressure that occurs in the contact zone of the seal and the floor is determined (Figure 6). The obtained data are used to estimate the area of contact of these elements.
In the simulation, two situations were considered: in the first, the coefficient of friction in the contact zone of the seal and the support surface was taken into account, and in the second – it was not. The values of the normal forces in the contact area and the area of the seal in contact with the support surface are shown in Table 1.

| Normal force, N | Contact area, mm² |
|----------------|-------------------|
| The coefficient of friction is equal to 0.6 | 0.22173 | 2.5 |
| The coefficient of friction is 0 | 0.31783 | 3 |

5.2 Calculated case 2

The study simulates the situation that occurs along the perimeter of the seal (Figure 7). Figure 8 shows a diagram of the deformation, and Figure 9 shows graphs showing the change in the clamping force, overpressure, and normal force in the contact area of the seal and the support surface.
Before the pressure is applied, the dependence of the normal force on the clamping mass is similar to that of the previous case. After applying the pressure, the normal force graph can be divided into two zones: before the pressure of 4650 Pa and after it. Up to this pressure, the value of the normal force remains almost constant. When this value is exceeded, the normal force begins to decrease.

![Figure 9. Graph of changes in the clamping force, overpressure and normal force during the simulation for calculated case 2](image)

This assumption is confirmed by modeling this problem without taking into account the graph of changes in the clamping force, overpressure and normal force during the simulation for calculated case 2; in the friction forces in this case, there is no zone with a constant value of the normal force.

| The coefficient of friction is equal to 0.6 | Normal force, N | Contact area, mm² |
|------------------------------------------|----------------|-----------------|
| 0.20757                                  | 2.5            |

| The coefficient of friction is 0         | 0.09483        | 2               |

Based on the study at different values of the coefficient of friction (Figure 10) between the support surface and the seal, it was found that with a decrease in the coefficient of friction, the duration of the "sticking" phase decreases, and with its increase – increases.

![Figure 10. Graph of the change in the normal force with different coefficients of friction](image)
The values of the normal forces in the contact area and the area of the seal in contact with the support surface are shown in Table 2.

5.3 Calculated case 3
The study is similar to the previous one, but the excess pressure acts not only on the outer surface of the seal, but also on the inner one (Figure 11). The deformation plot is shown in Figure 12, and Figure 13 shows the dependencies showing the change in the clamping force, overpressure, and normal force in the contact area of the seal and the support surface.

The nature of the obtained dependencies is similar to the second calculated case. A more thorough analysis shows that the final value of the normal force in the third calculation case is 205.61 N per 1 m of compaction. This is less than in the previous case by 2%.

Figure 11. Calculation scheme for case 3

Figure 12. Strain plot for the calculated case 3

The obtained result shows that such a scheme allows you to reduce the value of the normal force. Indeed, the reactions resulting from the action of pressure on the inner surface of the seal partially compensate for the force pressing the seal against the support surface. Obviously, this effect will be more significant with a higher-pressure value.

Figure 13. Graph of changes in the clamping force, overpressure and normal force during the simulation for calculated case 3
The values of the normal forces in the contact area and the area of the seal in contact with the reference surface are shown in Table 3.

| Normal force, N  | Contact area, mm² |
|------------------|--------------------|
| 0.20561          | 2.3                |
| 0.09029          | 2.2                |

5.4 Calculated case 4
This calculation case takes into account the process of movement of the mobile system on the front and rear seals (Figure 14).

Figure 14. Calculation scheme for case 4

When moving forward, the nature of the deformation of the rear seal is similar to the previous cases (Figure 15). For the front seal, the deformation pattern is different (Figure 16).

Figure 15. Plot of seal deformations for design case 4 (rear platform seal when moving forward)
Figure 16. Plot of seal deformations for design case 4 (front platform seal when moving forward)

Figure 17 shows a graph of the change in the normal force over time for different coefficients of friction. For all values of the coefficient of friction, a sharp decrease in the value of the normal force occurs at the initial moment. This decrease actually continues a similar graph obtained by modeling.
the second calculated case. Conventionally, the horizontal sections of the curves correspond to the state when the seal no longer deforms and slides along the support surface.

For small coefficients of friction, the inclined section of the curve is shorter, but this does not mean that the seal stops deforming earlier than that at higher coefficients of friction. Figure 10 shows that with a lower coefficient of friction, the decrease in the value of the normal force begins earlier.

![Graph of the change in the normal force for different coefficients of friction (rear platform seal when moving forward)](image)

**Figure 17.** Graph of the change in the normal force for different coefficients of friction (rear platform seal when moving forward)

Similar curves for the front seal are also shown in Figure 17. In this case, there is no phase of reduction of the normal force.

The values of the normal forces in the contact area and the area of the seal in contact with the support surface are shown in Table 4.

|                     | Normal force, N | Contact area, mm² |
|---------------------|-----------------|-------------------|
| Rear platform seal when moving forward | 0.0642          | 1.2               |
| Front platform seal when moving forward | 0.19672         | 1.8               |

6. Conclusion

It is established that in the absence of pressure acting on the seal, the value of the normal force is related to the force acting on it from the clamping side, a linear relationship. The value of the normal force is influenced by the coefficient of friction – the higher it is, the lower the value of the normal force. The reason for this phenomenon is the friction force that occurs when the seal is deformed, and holds it in place until a certain moment. In the absence of friction, this effect disappears and the energy that is "blocked" by the above effect passes into internal stresses.

When pressure is applied to the seal, the value of the normal force decreases by 10% compared to the data obtained in calculated case 1. The decrease is due to the fact that the pressure partially
compensates for the force acting on the clamping side. With an increase in the coefficient of friction, the value of the normal force increases.

The additional impact of pressure on the inner surface of the seal practically does not affect the result obtained in the second calculated case (the decrease in the value of the normal force was 2%). This effect may be more significant at higher overpressure values.

Analyzing the dependences obtained in the fourth study, we can note multiple peaks on the conditionally horizontal sections describing the normal force. They are the result of the seal sticking to the floor. This effect is associated with the transition from rest friction to sliding friction during movement and can be accompanied by such effects as noise or jerks. It is found that it is more pronounced at higher coefficients of friction, since the curve for this case has more pronounced fluctuations.

The results obtained make it possible to increase the efficiency of using mobile robotic platforms on an air cushion by accurately estimating the resistance forces at the design stage.

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