International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

September 2023 Issue 56 Volume 15 Number 3 Pages 59-67

EFFICIENCY INCREASING OF PERISTALTIC PUMP UNITS BY MODIFYING OF SQUEEZE ELEMENT MOUNT DESIGNING

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Abstract- Peristaltic pumps have many advantages, but the wear of the elastic element significantly reduces their service life. This study aimed to increase the working life and efficiency of the peristaltic pump unit (PPU) by reducing the resulting load jumps and wear factors. Investigation of the roller motions along the hose in PPUs given the liquid lubricant considered the viewpoint of solving the problem of unsteady elastic-hydrodynamic interaction of bodies in friction units. The study used an analytical solving method based on singular small parameter decomposition at the highest derivative and finite element method to obtain practical results. As a result, it was revealed that during the transient process, an unplanned doubled increase in the load leads to a short-term increase in the maximum pressure over the layer by more than an order of magnitude. To level out the load jump during the transition and to improve the wear factors of the roller mount, the design of the squeezing element mount was developed. The finite element calculation results are the maximum stresses, strains, and displacements of the pump design components loaded according to the calculation scheme. Replacement of the studied design with the developed one having the mount of squeezing elements increases the PPU working life and efficiency.

Keywords: Peristaltic Pump, Hose, Durability, Modeling, Optimization.

1. INTRODUCTION

At present, a variety of pumps exist for pumping various media [1] effectively used in different areas of industry, for example, in water supply, heating buildings, and industrial power systems [2, 3], in transporting all kinds of materials, waste removal of industrial enterprises, for supplying construction materials, lifting liquids to the required height, pumping sludge and water, and wastewater sampling [4, 6]. Pump units apply in oil and gas, chemical, construction, automotive, food industries, medicine, and others [7, 8]. There are dynamic pumps subdivided into vane and friction pumps (vortex, jet, airlift, and screw pumps), and volumetric pumps subdivided into diaphragm, piston, and rotary pumps [9, 10]. Volumetric pumps also include peristaltic pumps.

The object of this study is peristaltic pumping units (PPUs), more precisely - separate PPU components. In modern industry, PPUs provide an opportunity to pump viscous, abrasive, chemically aggressive media, etc. [11]. Their main feature is the absence of contact of the medium with the structural components of the unit itself. The advantages of this pump include accurate medium dosing, easy installation and replacement of components, tightness of the system, and the possibility of working with aggressive media and media with various inclusions [12]. Besides its advantages, PPU has disadvantages, such as temperature range limitations (from 0° C to 90° C), low productivity when pumping viscous media, pulsations at low rotor speed, and the most important one – elastic element wear [13]. Improving the efficiency, reliability, and durability of PPU relates to increasing the working life of an elastic element - a hose through which the pumped medium flows. Rapid hose wear at numerous cycles of compression can lead to the failure of the entire unit [14], which determines the relevance of works aimed at improving the hose's reliability and durability. The subject of the research is the dependence of the hose element durability on the operating parameters of the pump unit. This work aims to increase PPU service life and operating efficiency by reducing load jumps and wear factors.

2. LITERATURE REVIEW

Completely different papers discuss peristaltic pump designs and their characteristics; some aim to increase PPU service life [15]. In several works, the authors propose modernizing the hose design [16]. There are also studies on using alternative materials for manufacturing the hose [17]. Many of these ways of increasing working life complicate PPU production significantly. Therefore, it is relevant to develop alternative approaches to increase hose durability.

In several research works, the authors consider the pump's technological capabilities and hydraulic characteristics, including the performance of the squeeze rollers, and conclude about the relationship between mixture flow pulsation and working life [18, 19]. The authors of [15] consider the issue of reducing mixture flow pulsation in pumps. One of the ways to reduce the negative impact of this phenomenon is to increase the number of pump squeeze rollers, but this method significantly reduces the service life of the working part of the hose in the pump housing [20]. Another practice could be to use the classic control methodology with a feedback mechanism. However, this method leads to an increase in the injection pressure of the transported solution. In work [21], the authors optimized fluid flow pulsation and its parameters, which increased working life. However, the study set specific parameters of the working medium not applicable to our work.

Another approach to solving the problem is to analyze static and dynamic stresses, study the characteristics of pulsating flow, pressure pulsations, and the effect of mechanical loads on the elastic PPU element, and apply various alternative methods of volume flow modeling [22]. One of the most efficient modern calculation methods is simulation modeling in software using the finite element method (FEM) [17-25].

However, the currently known developments cannot fully solve the problem related to the wear of the elastic element during interaction with the working body of the pump. Therefore, the joint analysis of the rotor roller motions along the work envelope in PPU simultaneously using analytical method and FEM can refer to a new combined approach to solve the set problem of improving the working life [26, 27]. Studies based on the proposed combined approach make it possible to develop the design of the squeezing element mount with further calculations of the stress-strain state to confirm the result [27].

3. OBJECTS AND RESEARCH METHODS

3.1. Description of PPU Design

The PPU design (Figure 1) provides easy installation, maintenance, and repair. The PPU operates as follows. An electric motor drives the rotor. As it rotates, a shoe mounted on the rotor presses the hose tightly against the track, blocking the passage and forming a locked area. Pressure starts to increase in the flattened area, pushing the fluid through the hose toward the pressure side. As the shoe rotates along the track in the deformation zone, the hose starts to return to its former shape, its volume in the straightening area increases, and the pressure decreases, resulting in a discharge, which contributes to the suction of a new portion of the pumped medium. The cyclic alternation of these areas ensures pumping stability.

PPUs pump various media in different industries (food, chemical, pharmaceutical, construction, etc.) without damaging their structure. For example:

- Chemically active media
- Highly viscous, viscous, and low-viscosity media
- Medicines and solutions
- Abrasive media
- Media containing foreign inclusions
- Explosive solutions

A PPU design developed as part of this work includes the following components:

- Support frame
- Induction motor
- Mount
- Peristaltic pump
- Control panel

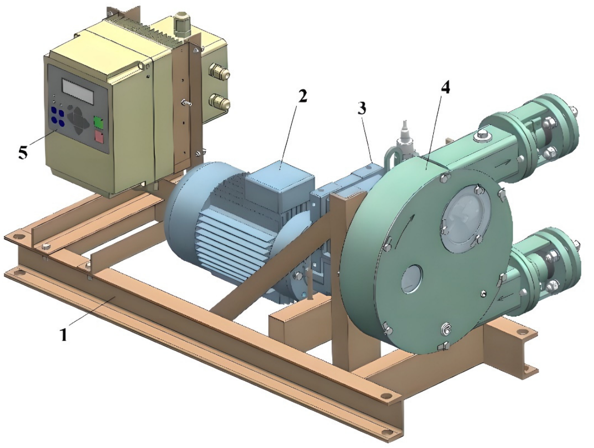

Figure 1. PPU design: 1- frame, 2- electric motor, 3- mount, 4- peristaltic pump, 5- control panel

The support frame (Figure 2) is a welded metal structure of standardized profiles. The frame holds the PPU components and allows the pump unit installation on the horizontal plane at the place of operation. The support frame structure consists of base 1, on which two racks 2, installed by welding for peristaltic pump connection and beam 3 for induction motor installation with the mount. In addition, on the base, there is rack 4 for control panel fixing by bolted connection.

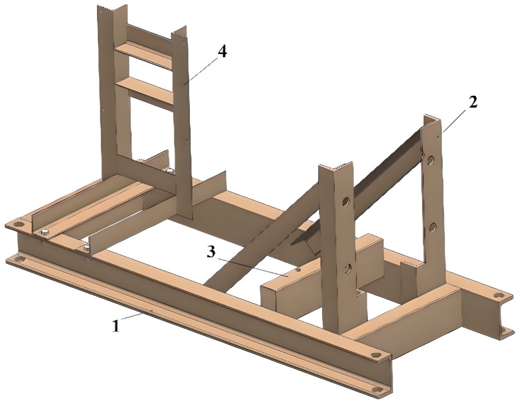

Figure 2. Support frame: 1- base, 2- rack for peristaltic pump connection, 3- beam for electric motor installation with mount, 4- rack for control panel fixing

The induction motor converts electrical AC power into mechanical one driving the entire mechanism. It differs from other types by its relatively low noise level and long service life. The mount connects the motor and peristaltic pump and provides self-centering of the constituent components and their rigid fixation relative to each other.

The peristaltic pump (Figure 3) is the primary PPU actuator. It consists of housing 1, which contains hose 2, squeezing element 3 with the shoe, and housing cover 4, connected to housing 1 by bolted connection 5. Arrows 6 on housing 1 and cover 4 show the direction of transportation. The core of the squeezing element in contact with the hose is the shoe rigidly fixed to the rotor. Such design ensures the same compression force on the hose along its length and independence of PPU operation from the pressure of the pumped medium.

The control panel designed to control the electric motor consists of means for starting and stopping, selecting and adjusting the rotation speed, torque control, and overload and fault protection. Figures 4-5 show the upgraded design of the squeezing element. The squeezing element of the peristaltic pump is rotor 1, mounted on base 2 using rolling bearings 3 installed on the base shaft and fixed by a shoulder on one side and by ring-type stopper 4 on the other. The squeezing elements of the structure - shoes 6, connect to rotor 1 by bolted connection 5. Figure 4 also shows the torque transfer from the shaft to the rotor through the spline joint with the help of cover 7, connected to the rotor through bolted connection 8.

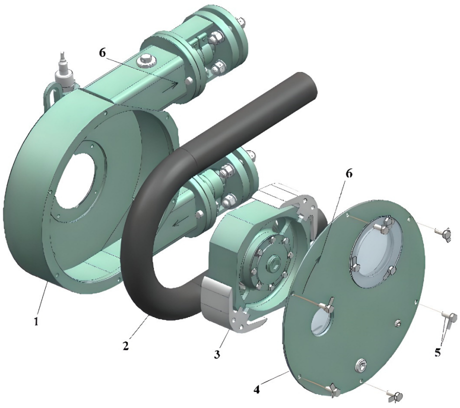

Figure 3. Peristaltic pump: 1- housing, 2- hose, 3- squeezing element, 4- housing cover, 5- bolted connection elements (bolt, locking washer), 6- direction of transportation

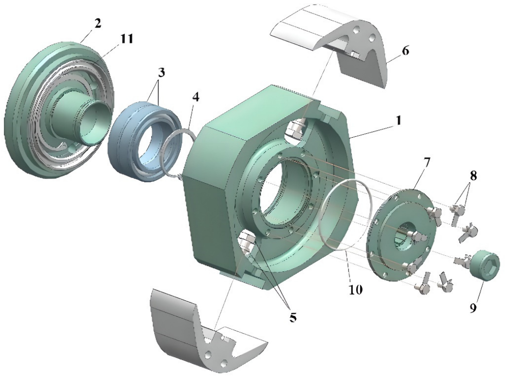

Figure 4. Squeezing element: 1- rotor, 2- base, 3- rolling bearings, 4- locking ring, 5- bolted connection elements (bolt, split washer), 6- shoe, 7- cover, 8- bolted connection elements (bolt, locking washer), 9- plug, 10- O-ring, 11- sleeve

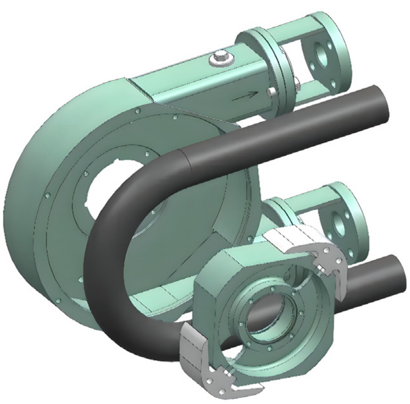

Figure 5. Squeezing element design of the PPU structure

3.2. Research and Design Analysis Methodology

Investigation of the rotor squeezing element motion processes along the working surface of the hose, taking into account the lubricant, considered the viewpoint of solving the problem of unsteady elastic-hydrodynamic interaction of bodies in friction units. The study applied an asymptotic analytical solving method based on singular small parameter decomposition at the highest derivative and the calculation by the finite element method to obtain practical results. Using these methods is necessary to determine the effect of squeezing elements in the form of rollers on the hose working life and makes it possible to determine the maximum stresses, strains, and displacements of the pump structure components loaded according to the calculation scheme. The calculation of the stress-strain state of the PPU structure is necessary to determine the most stressed areas at various points of the unit operation. Figure 6 shows schematically the interaction of a cylindrical roller and a solid surface coated with a lubricant.

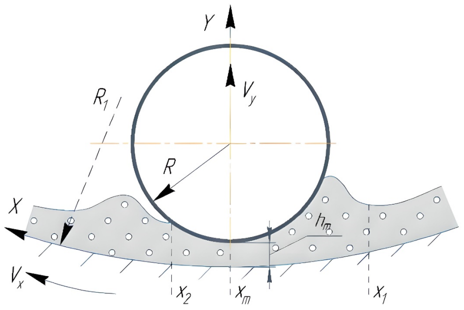

Figure 6. Schematic arrangement of the roller and liquid lubricant layer

The primary calculation cases for the asymptotic analytical method are steps I-III.

I. Calculation of the pressure in the lubricating layer

An idealized model of the roller contacts with a surface having an applied lubricant layer with a constant viscosity coefficient was considered. In this case, the Reynolds equation describes the pressure distribution [28].

$$\frac{\partial}{\partial x}\left(h^2\frac{\partial P}{\partial x}\right)=6\mu V\left(\frac{\partial h}{\partial x}+\frac{2}{V}\frac{\partial h}{\partial t}\right) \tag{1}$$

where, P is the pressure in the layer on which the lubricant is applied, μ is the dynamic oil viscosity at normal pressure, V is the tangential speed of the roller relative to the surface, h is the thickness of the lubricant layer, depending on the surface deformation The x axis is oriented along the contact surface. Here, a reference system is used where the roller has zero tangential velocity and X is the direction of surface motion.

II. Determining the damping factor of the lubricating layer

Determining the bearing capacity as a function of the parameter υ used the obtained pressure distributions [29]:

$$W'(\upsilon)=\int_a^c q(x,\upsilon)dx \tag{2}$$

III. Investigation of the non-stationary process

To study the non-stationary process, an equation is used that describes the roller motion in the direction of the normal to the surface [28]:

$$m\frac{d^2h_m}{dt^2}+\lambda(h_m)\frac{dh_m}{dt}-W_0(h_m)=-F \tag{3}$$

The main difference of FEM, a numerical method for approximate solution of physical problems, from the classical algorithms of variational principles and residual methods is the choice of basic functions taken as piecewise continuous functions, which are zero-turned everywhere except for bounded subdomains, which are finite elements. This leads to a band-sparse structure of the coefficient matrix of the resolving system of equations.

Among the main advantages of FEM are:

1. The ability to investigate objects of any shape and physical nature – solid deformable bodies, liquids, gases, and electromagnetic media;
2. Different shapes and sizes of finite elements;
3. The ability to investigate homogeneous and inhomogeneous, isotropic and anisotropic objects with linear and non-linear properties;
4. The ability to solve both stationary and non-stationary problems;
5. The ability to solve contact problems;
6. The ability to simulate different boundary conditions;
7. Convenience for computer programming;
8. Solving different physical problems using the same finite-element mesh, which simplifies the analysis of related ones;
9. Economic sparse symmetric band "stiffness" matrix of the resolving system of equations, which speeds up the computational process on a computer;
10. Convenient implementation of hierarchical discretization of the investigated domain into subdomains with forming superstructures that makes it possible to use parallel problem solving efficiently.

The FEM basis is the investigated domain partition into a finite number of sections - finite elements. The finite elements can have different shapes and sizes. The partitioning results in a finite element boundary mesh with nodes on the boundaries of the finite elements where the values of the required function are determined. Neighboring elements share common nodes. Additional nodes can also be created within the elements and on their boundaries (Figure 7) [30].

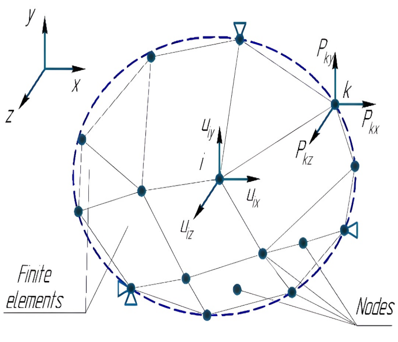

Figure 7. Finite element model [30]

Mesh generation is one of the most essential steps in accurate finite element modeling. The choice of the shape and type of finite elements (FEs) depends on the shape of the studied body and the way of its loading.

Rod FEs applies if the object has a beam structure and all its components work in tension, compression, torsion, and bending. Flat FEs are necessary when the studied body has a plane stress-strain state and the shell shape, volumetric ones - for analysis of volumetric bodies and stress state. It is also worth considering breaking places with expected high-stress gradients into smaller FEs or FEs of a higher order. All elements and nodes have numbers. Node numbering can be general (global) for the entire finite element model and local within the elements. It is desirable to number the elements and nodes in general numbering so that the complexity of calculations is the least. There are algorithms for optimizing this numbering by determining arrays of connections between numbers of elements and general node numbers and between the latter and local numbers.

There are the following meshes.

- Tetrahedral meshes based on tetrahedral (tet) elements.
- Hexahedral meshes based on hexahedral (hex) elements.

Building a mesh based on hexahedral or "brick" elements usually gives more accurate results with fewer elements than tet elements. However, in the case of complex geometry, it is better to choose tet elements.

- Hybrid meshes.

You can use the Multizone method in ANSYS Mechanical. It is a hybrid of hex and tet elements, making it possible to create different parts of the geometry using various methods, accelerate the geometry preparation step, and manage element sizes more flexibly, locally, and across the entire volume.

Sweep meshing actually "sweeps" the volume and faces along some kind of guide, which helps build a regular mesh. The choice of meshing method usually depends on the type of analysis (explicit or implicit) or physics you are working with, as well as the level of accuracy you need to achieve. There are several other options - Cartesian or tetrahedral meshing used for specific types of analysis, for example, in additive manufacturing.

Mesh controls help get a higher-quality mesh. ANSYS Mechanical makes it possible to perform local mesh adaptation vs. working with a global mesh size. Local controls include local resizing, level of geometry detail based on element size, the area of adaptation, and others. A high-quality mesh is necessary for more accurate results because a poor mesh can cause difficulties in achieving convergence leading to incorrect results and false conclusions.

An essential aspect of preparing a CAD model is to describe the relationship between two or more elements of geometry. For example, if the geometry elements have common nodes or sides (edges), it is essential to decide whether it will be a conformal or nonconformal grid. Conformal mesh applies to parts joined by glue or welds, and nonconformal mesh - by contacts or welds. The calculation goal is to determine the stress concentrators in the model volumes and the most stressed components of the structure. When using software for FEM modeling, it is essential to determine which CAD model elements need transfer and which do not. Often the CAD geometry created for production purposes is too complex and detailed. Not all parts may be necessary for the simulation, so some are removed to save time.

The stress-strain analysis optimized the three-dimensional geometric model of the PPU by excluding insignificant unloaded and small elements (rounding's chamfers, fixing holes, and others) that do not affect the final calculation result. To save time, calculations used an incomplete hose model and considered the rotor a rigid body not participating in calculations. Based on this, the calculation scheme of loading was finally developed (Figure 8), with the free end of the hose and the outer surface of housing fixed and the adhesive contact installed between the housing and the hose. The shoe rotates around the rotor axis simulating only the first 40° of rotation, there is a frictionless contact between it and the housing.

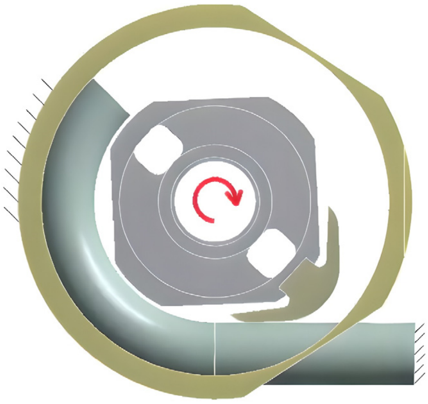

Figure 8. Calculation scheme

In addition, modeling involved the following assumptions:

- Materials are solid and homogeneous;
- The chemical composition and aggregate state of the materials are unchanged during the calculation process;
- There are no heating processes due to deformation;
- There are no outside influences on the base;
- The material used for the hose was rubber, and for the structural parts - 08Cr18Ni10Ti.

To evaluate the strength characteristics of the pump and confirm its reliability and efficiency, simulation modeling the first 40° of the shoe rotation around the rotor axis in 10° increments and an adjustable finite element mesh partitioning of the geometric model were performed for the numerical solution (Figure 9).

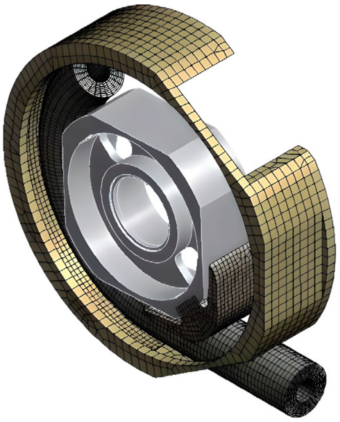

Figure 9. Distribution of finite elements in the volume of the pump unit

4. RESULTS

Finite element calculations yielded the following results:

- The contact surface of the hose experiences stresses up to 0.042 MPa when the shoe rotates 40° (Figures 10-11).

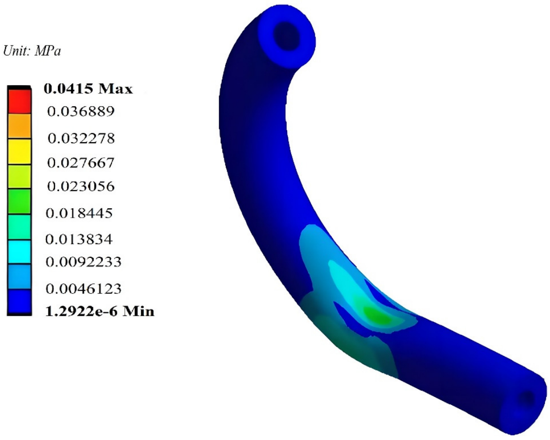

Figure 10. Distribution of equivalent stresses in the hose

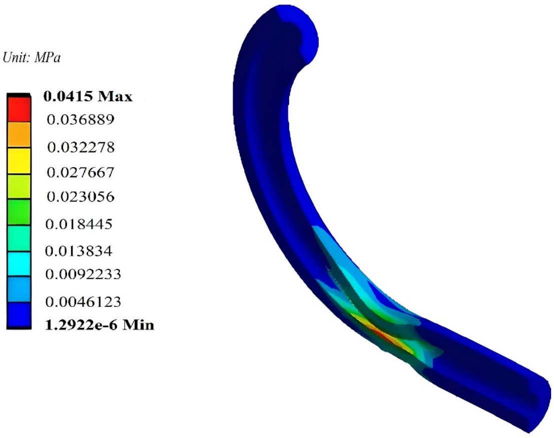

Figure 11. Distribution of equivalent stresses in the hose section

- Strains in the hose volume are up to 0.548% when the shoe rotates 30° (Figures 12-13).

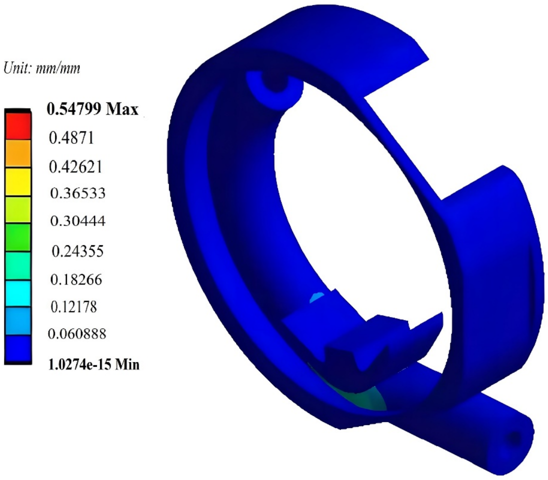

Figure 12. Distribution of equivalent strains in the pump unit

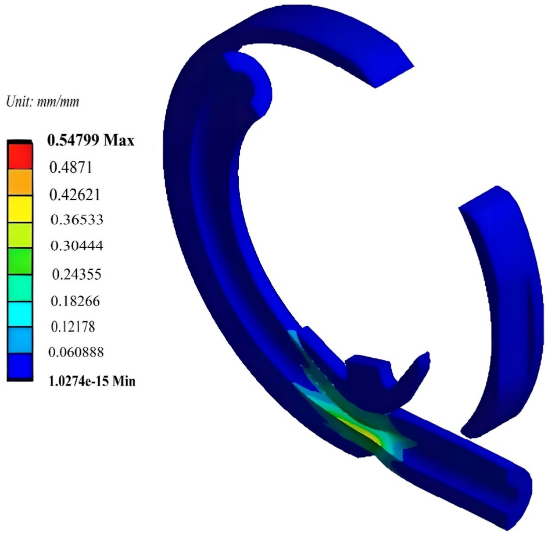

Figure 13. Distribution of equivalent strains in the pump unit section

- Maximum displacement in the hose is 24.676 mm when the shoe rotates 40° (Figure 14).

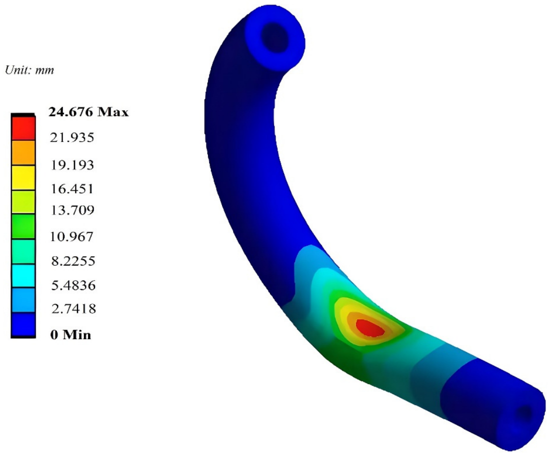

Figure 14. Distribution of displacements in the hose

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- Maximum stress in the shoe volume is 0.068 MPa when the shoe rotates 40° (Figure 15).

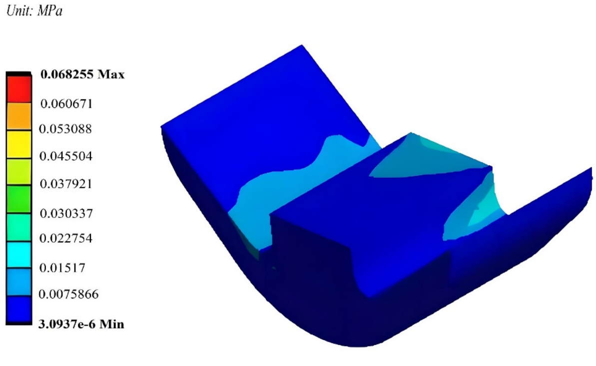

Figure 15. Distribution of equivalent stresses in the shoe

- Maximum strain is 0.393×10^{-6} % when the shoe rotates 40° (Figure 16).

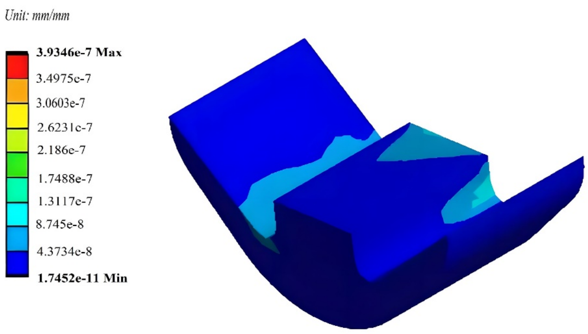

Figure 16. Distribution of equivalent strains in the shoe

- Displacement in the hose volume is 89.609 mm when the shoe rotates 40° (Figure 17).

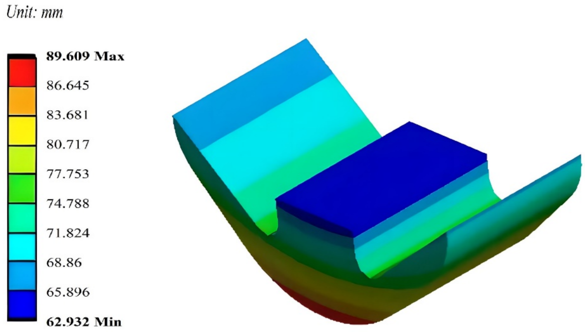

Figure 17. Distribution of displacements in the shoe

- Maximum stress on the housing is 0.146 MPa when the shoe rotates 30° (Figure 18).

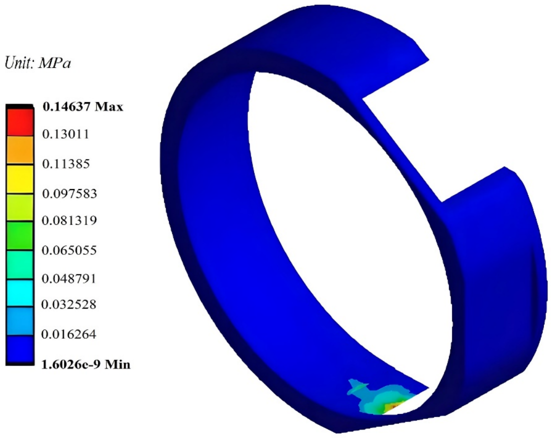

Figure 18. Distribution of equivalent stresses in the housing

- Maximum strain in the body is 0.946×10^{-6} % when the shoe rotates 30° (Figure 19).
- Maximum housing displacement is 2.611×10^{-5} mm (Figure 20).

The calculation results make it possible to conclude that the developed PPU design is efficient under the most stressed operating conditions. Using the shoe as a squeezing element reduces the load on the mount, thereby increasing the working life of the critical heavy-loaded components of the PPU.

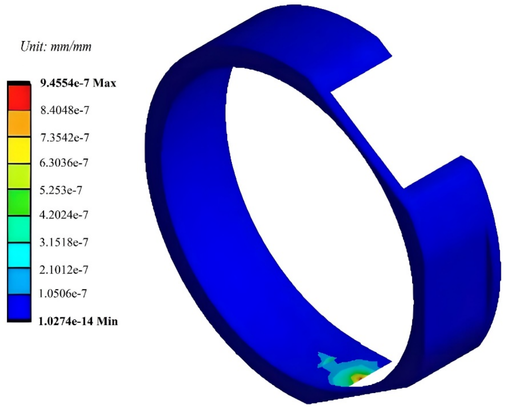

Figure 19. Distribution of equivalent strains in the housing

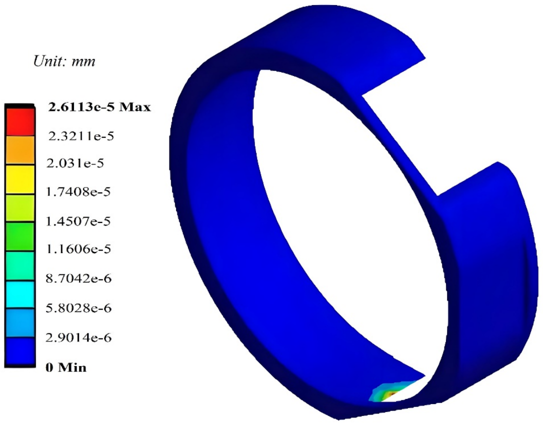

Figure 20. Distribution of displacements in the housing

5. DISCUSSION

The main results of the finite element calculation are the maximum stresses, strains, and displacements of the pump structure components loaded according to the calculation scheme.

The finite element method yielded the following results. The maximum stress on the hose contact surface is 0.042 MPa, and the maximum displacement in the hose is 24.676 mm at the rotor rotation angle of 40°. The maximum strain in the hose volume is 0.548% at the rotor rotation angle of 30°. The maximum stress in the shoe volume is 0.068 MPa concentrated on the contact surface, indicating that the load on the mount reduces. The maximum strain is 0.393×10^{-6} %, and displacement is 89.609 mm at the rotor rotation angle of 40°. The maximum stress on the housing at the rotor rotation angle of 40° is 0.146 MPa concentrated in the contact area with the hose, and the maximum strain is 0.946×10^{-6} %. The maximum displacement at the rotor rotation angle of 30° is 2.611×10^{-5} mm.

These finite element calculation results showed that the values of maximum stresses of the pump components are significantly below acceptable, proving the efficiency of the developed design. The results obtained during the study, namely, the maximum stresses, strains, and displacements, help to evaluate the efficiency of the new squeezing element mount design. Compared to the standard design, the upgraded squeezing element design helps to achieve significantly better performance.

6. CONCLUSION

6.1. Findings of the Study

The results obtained during the study help to evaluate the efficiency of the developed design of squeezing element mount. The asymptotic analytical calculation revealed that using the initial design with rollers as squeezing elements causes sudden pressure jumps more than twice occur, leading to premature wear of the friction node.

6.2. Strengths and Limitations

The strength of the developed design is the increased service life and performance of the PPU by reducing occurring load jumps and wear factors achieved by replacing the initial investigated design with the developed one of squeezing element mount. To confirm the efficiency of this design, stress-strain calculations involved finite element analysis. The scope of application limits new design because a rigidly fixed squeezing element can damage the hose when pumping abrasive media.

6.3. Theoretical Significance for Future Research

The theoretical significance of this work is that its results can further improve design, for example, upgrading the hose or housing.

6.4. Practical Importance

The practical importance of this work is that the results of finite element calculation made it possible to conclude the efficiency of the developed PPU design under the most stressed operating conditions. Using the proposed design of the squeezing element makes it possible to reduce the load on the mount, thus increasing the working life of the critical heavy-loaded components of the PPU. The above confirms the readiness of the developed design for production and industrial implementation.

ACKNOWLEDGEMENTS

This work was done in the Federal State Budget Educational Institution of Higher Education "MIREA – Russian Technological University" (RTU MIREA) with the financial support of the Ministry of Science and Higher Education of Russia under the project No. 075-11-2022-027 on the topic: "Creating high-tech mass production of peristaltic pump units for aggressive media with enhanced performance".

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