Optimization of a Polymeric Rod from Plants Conveying Equipment

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This paper presents a procedure for the calculus and dimensional optimization using finite elements analysis of a polymeric retractable rod which replaces a metallic one. This rod is an element of the front auger embedded in a technological equipment. The mechanism is 3D modeled in SolidWorks. CosmosMotion is then used to simulate and analyze the motion of the mechanism and to calculate the loads acting on the rod during its movement. These loads are then exported in CosmosWorks – a finite elements analysis software – which is used here to perform stress analysis and to optimize the retractable rod's dimensions.

Keywords: polymers, optimization, finite elements analysis

One of the main factors machine-building industry permanently focuses on is the reduction of the total cost of the fabricated component. Usually, another important objective is the mass reduction of the entire product. Both of the above mentioned demands can be greatly influenced from the materials' selection stage. Frequently, metallic parts are replaced with plastic ones when possible. Obviously, the final machine component must meet the functional requirements without diminishing its safety. From this point of view, strength, rigidity, relative reliability and durability are traditional key factors. Another emergent requirement that most of the plastics also met is recyclability, which indirectly ads its contribution to further costs reduction.

This paper presents a design procedure for dimensional optimization of a the plastic retractable rods embedded in the front auger of a technological equipment. Some of the foreign manufacturers have already replaced the metallic ball joints which are guiding these rods, with polymeric or composite ones. The most adequate polymers are analyzed and compared, taking into consideration their following properties: mechanical strength, friction coefficient, wear resistance, moisture absorption, linear thermal expansion coefficient, chemical resistance to oils and lubricants and machinability.

The model

Figure 1a shows the 3D model of a simplified mechanism comprising the retractable rod. During operation, the cylindrical case *a* of the auger rotates clockwise with of 180 rpm around the axle *e*. On the lower part of its trajectory, the retractable rod *d* pushes vegetal material towards another transporter placed on the back side of the platform *g*, which is not represented here. Due to the offset between the axles *e* and *f*, the rod *d* retracts inside the cylinder *a* in the superior part of the trajectory, thereby losing its contact with the plants. The sphere *b* from the ball joint, which guides the retractable rod *d*, is fixed by means of the spherical case *c*. The dimensions of the entire mechanism correspond to the real ones, being represented at 1:1 scale. Figure 1b shows a more detailed section view of the ball joint's area.

One of the parameters that must be calculated before computing the motion simulation, is the vegetal mass rate undertaken by one rod. According to the instruction book, 7 kg/s is the maximum mass rate that can be processed by the entire equipment. As the transporter has 11 retractable rods, it is simple to calculate that each rod must ensure a mass rate of maximum 0.64 kg/s. The mass m_d of vegetal material pushed by one rod in the course of one rotation is:

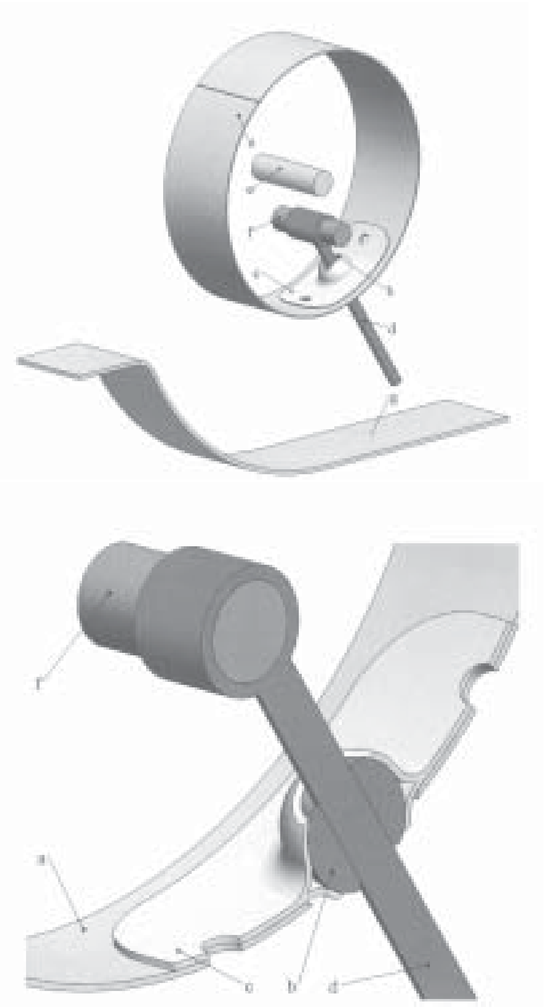

Fig. 1. The simplified model of the analyzed part
a –complete model; b – section view (detail)

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$$m_d = \frac{60 \cdot Q_{tr}}{n} = \frac{60 \cdot 0.64}{180} = 0.213 \text{ (kg/rot)},$$

where n is the transporter's rotative speed (rpm).

Material selection

Taking into account the operating conditions and types of stresses acting on the rod, there were considered in a first stage those polymers that would successfully bear up [1-3].

Acetals and polyacetals combine very high strength and good abrasion and temperature resistance. They have very good dimensional stability and low coefficient of thermal expansion. Except for strong acids, they prove out good chemical resistance.

Polyterephthalate (PETP) and modified versions have high rigidity, strength, abrasion and chemical resistance, and low friction coefficient. The chemical agents that attack them can't be found among those that belong to the specific environmrnt of the spherical joint studied. They have fair to good resistance to oils, grease and fuels.

Polyamides: nylon is among the toughest engineering polymers, with high abrasion resistance and very low friction coefficient. As it proves high load capacity, it can be used for high-speed bearings. In its geniune form, it is a hygroscopic material. Chemical resistance is good. It is recommended to be filled with powdered molybdenum disulfide or graphite when used for manufacturing bearings, cams, gears etc. Due to moisture absorption, unfilled nylon is prone to swelling.

Aliphatic Poliketones have mechanical, physical and thermal properties similar to polyamides and polyacetals. Their high levels of strength, stiffness and toughness are preserved over a broad temperature range. They have a low coefficient of friction and also a low wear factor against steel.

Polycarbonates are noted for their remarkably strength and dimensional stability. On the other hand however, polycarbonate can be extremely fragile if it is not dried adequate. Although, they are not considered to belong to very high chemical resistance polymers.

Polysulfones are tough, strong and stiff polymers. They have excellent dimensional stability and good chemical resistance. Glass fiber improves mechanical strength. Polysulfones are used in engineering areas similar to those of nylon. Aromatic polysulfones proved to have high thermal stability. The polymer's degradation process starts

Table 1

MEAN VALUES OF THE PROPERTIES OF STUDIED POLYMERS

Properties	Polyacetal	Polyterephthalate	Polyamides Naylon	Nylon PA66 30% graphite
Modulus of elasticity (GPa)	2.66	2-4	1.6-3.8	22 – 23.5
Ultimate tensile strength (MPa)	24-137	80	90-166	191 – 242
Ultimate elongation (%)	15-75	-	50-300	1 – 4
Yield stress (MPa)	62-83 (compr:85)	72.5	80-90	166 – 201
Yield strain (%)	9	-	3.8	-
Rockwell hardness	M94, R120	R101, M94	M85, R117	M106, R120
Specific gravity	1.43	1.3-1.4	1.13-1.15	-
Thermal expansion coefficient (10^{-5},C)	8.1	2 – 8	8.0	11 – 16
Chemical resistance to oils and fuels	Good	Fair	Good	Good
Machinability	Good	-	FB	Inj. molding
Friction coefficient (st.-static; dyn.-dynamic)	st.:0.183 dyn.:0.127	0.2 – 0.4	0.26-0.42	0.15

Properties	Poliketone	Polycarbonates	Polysulfone	Polyphenylene Oxide
Modulus of elasticity (GPa)	>3.6	2 – 2.24	4.87	2.53
Ultimate tensile strength (MPa)	108 (compr:123)	55-65	93	53.1 (compr:91)
Ultimate elongation (%)	35	20-100	24.8	50
Yield stress (MPa)	103	55	88 (compr:84.4)	51.7
Yield strain (%)	5.19	-	5.77	14.8
Rockwell hardness	M99, R125	M70-M180	M85, R123	R116
Specific gravity	1.2 – 1.3	1.2	1.22-1.57	1.08
Thermal expansion coefficient (10^{-5},C)	9-11	6.6	4.6	6.7
Chemical resistance to oils and fuels	Good	Poor	-	-
Machinability	Good	Very good	-	-
Friction coefficient (st.-static;dyn.-dynamic)	st.:0.11-0.4 dyn.:0.272	-	0.28-0.45	-

at about 500-600 °C. They also have good chemical and hydrolythic stability in case of sudden *p*H variations [4].

Polyphenilene oxides have superior mechanical properties, similar to those for nylon, however with very little moisture absorption. It can be injection molded. In order to reduce its cost, it is frequently available blended with polystyrene.

In order to have a first impression regarding the material that should be chosen, summarizing table 1 was elaborated with mean values of the significant properties for this study [1,5-7]. These values should be considered as a rough guide, as they can be affected by additives, processing methods, shape of the part, period of force action and loading speed [8].

Due to their properties, polyamides and polyketones are good candidates to be used in this analysis. For wear-resistant applications, nylon's and polyketone's toughness, low coefficient of friction and good abrasion resistance make them ideal replacements for metallic materials. However, there are two reasons connected to the studied specific operating conditions that allow choosing between these two polymers: continuous service temperature (CST) and moisture absorption. While for nylon 6/6, the long-term temperature limit is 100^{0}C, the CST for polyketones is more than double (approximately 248 °C) [7]. On the other hand, nylon is one of the highest hygroscopic polymers. Its strength and wear resistance decrease with increased water content [9]. At 50% relative humidity, the nylon's mass increases with up to 2.5% in 24 h due to moisture absorption, compared while only 0.1% for polyketones in the same conditions.

Taking into account these considerations, a polyetheretherketone was selected for the studied retractable rod. Its exact properties are presented in table 2 [10].

Table 2

PHYSICAL, MECHANICAL AND THERMAL PROPERTIES OF THE SELECTED POLYETHERETHERKETONE

Properties	**Units**	**Values**
Physical		
Density	g/cm^3	1.32
Water Absorption (24 ore)	%	0.5
Mechanical		
Tensile Strength (yield)	MPa	96
Tensile Modulus	GPa	3.6
Ultimate Elongation	%	50
Flexural Strength	MPa	191
Flexural Modulus	GPa	3.654
Compressive Strength	MPa	118
Ultimate Shear Strength	MPa	52.4
Izod Impact Strength (1/8" thick specimen)	J/cm	0.8
Rockwell Hardness		M99
Coefficient of friction (0.5 m/s, 70 kg load)	µ	0.18
Thermal		
Maximum CST	^{0}C	250
Melting Point	^{0}C	334
Processing temperature	^{0}C	193-221
Thermal Expansion Coefficient	mm/mm	0.08-0.12

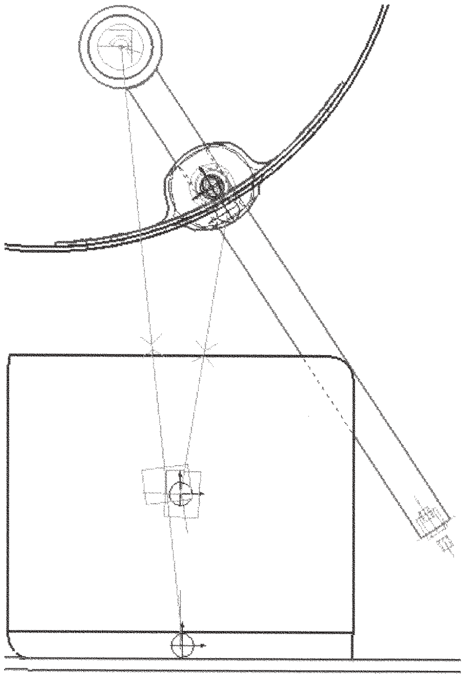

Fig. 2. Pozition corresponding to the maximum load acting on the retractable rod

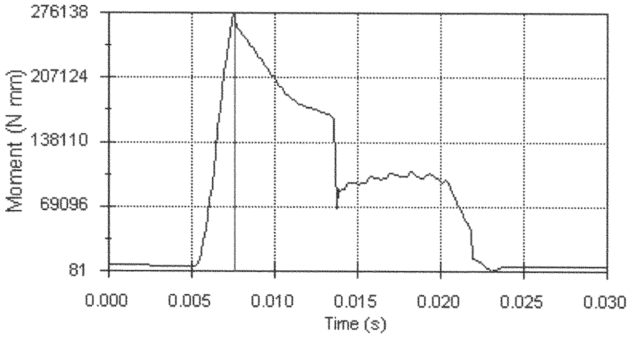

Fig. 3. Variation of the reaction moment acting on the rod in the ball joint

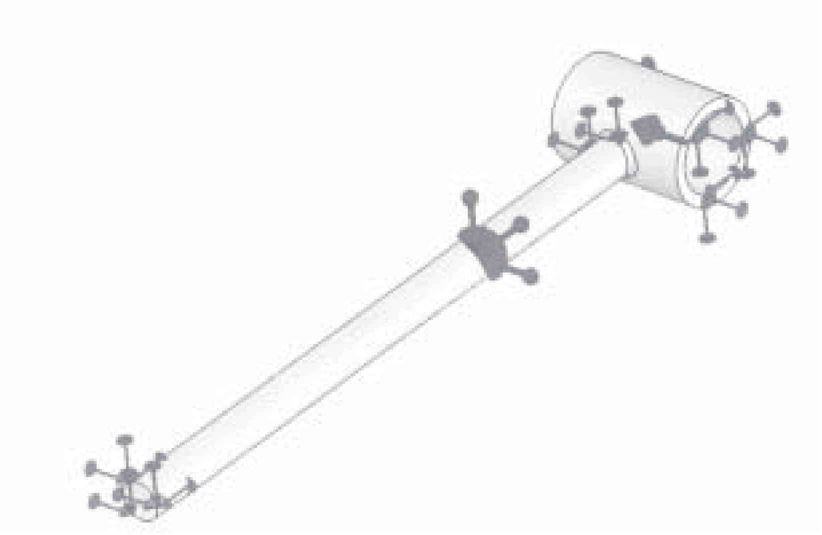

Fig. 4. Distribution of the computed static and dynamic loads on the retractable rod

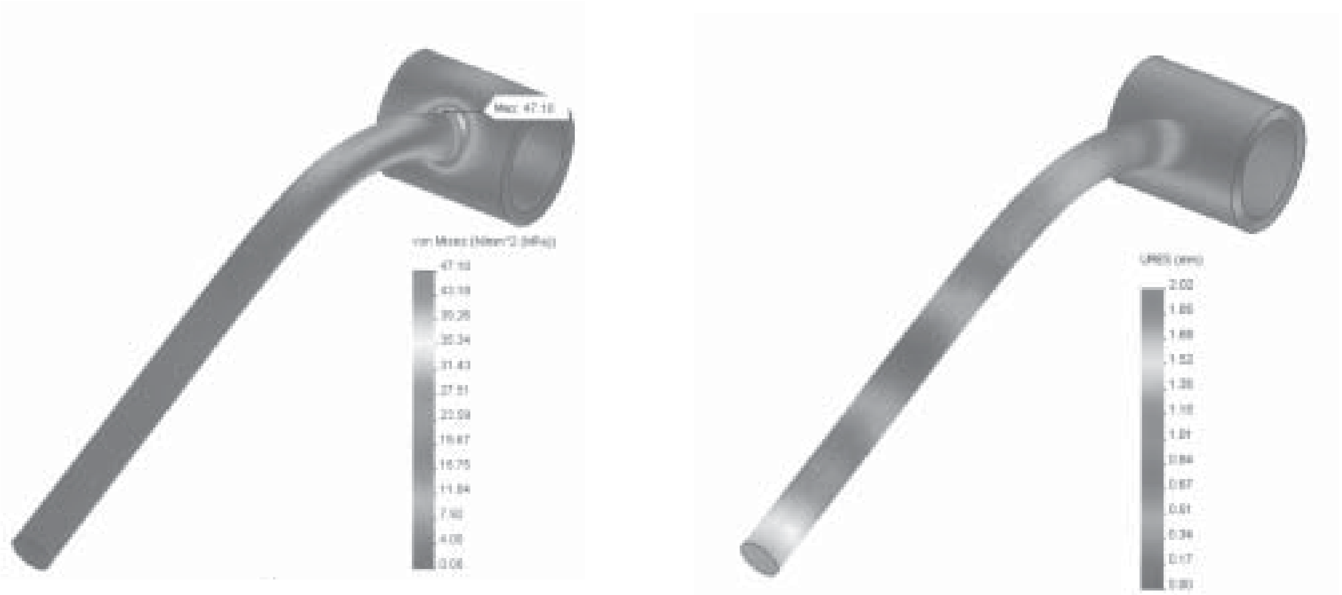

Fig. 5. Distribution of the von Mises stresses (a) and displacements (b) on the rod

Mechanism's dynamics simulation

A cuboid is added to the mechanism from figure 1. It is placed on the platform and symbolizes the mass of vegetal material pushed by one rod in the course of one rotation. The following properties necessary for the simulation were attached to the cuboid [11]:

- mass: 0.213 kg
- density: 100 kg/m^3
- coefficient of friction with steel plate:
(for 17% plants humidity): 0.56 (static) 0.39 (dynamic)
- coefficient of elasticity k: 1.5 N/cm
- damping factor c: 2 Ns/cm

Values of friction, damping and elasticity coefficients are the upper limits of their intervals, in order to simulate the most difficult running conditions.

A revolution of 19 rad/s is specified for the cylindrical case. The simulation lasts for 0.1 s. The program computes the kinematic and dynamic parameters of the mechanism. Figure 2 shows the moment right before the cuboid begins to move. It can be noticed that, due to the small value of the elasticity coefficient, the retractable rod penetrates the mass of plants until the static friction force between the cuboid and the platform is overcome. This is the limit moment, when the reaction forces acting on the rod have maximum values, as it is proved out by the example graph from figure 3.

Analysis and Optimization

The finite elements analysis software CosmosWorks is used to calculate the retractable rod's behavior under the action of previously computed reaction forces and moments (fig.4).

Before the analysis, the material properties specified in table 2 are assigned to the part. The three-dimensional model is meshed with high quality parabolic tetrahedral elements, with nodes both at corners and at the middle of each edge. Automatic transition function is used in order for the program to automatically refine mesh elements in the area of small features and other fine details of the CAD model. Stress and displacement distribution computed during the structural analysis are presented in figures 5 a, respectively b. One can notice that the maximum Von Mises stress (47 MPa) is much lower than the tensile strength at yield of the used polymer.

Based on the analysis results, parameters that will be used on the optimization procedure must be defined. The procedure must configure a rod with minimum mass, so that the maximum displacement should not exceed 1.5 mm by more than 5%. Table 3 presents the dimensions that can be modified (fig.6) as well as their upper and lower limits.

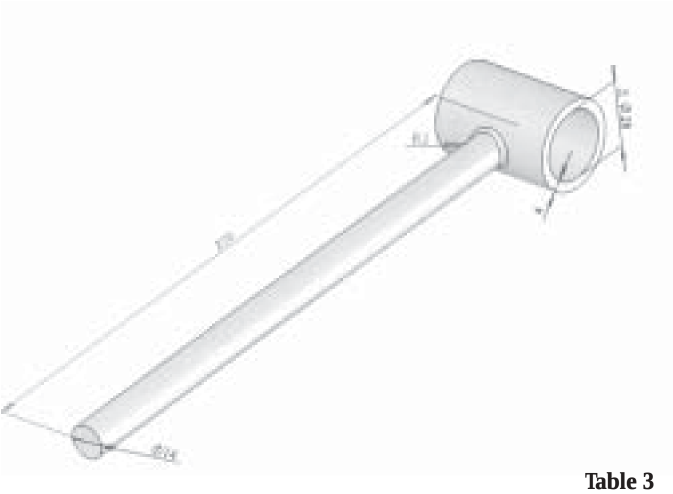

Fig. 6. Dimensions of the non-optimized retractable rod

Table 3

VALUES RANGES OF THE VARIABLE DIMENSION

Dimension	Initial Value	Lower Bound	Upper Bound	Convergence Tolerance
Diameter of Rod (mm)	14	14	26	1 %
Fillet Radius (mm)	2	2	6	1 %
Hub Thickness (mm)	4	3	7	1 %

Conclusions

The optimization process was finalized in 14 iterations. According to expectation, the maximum displacement appears on the tip of the rod, however with a value of 1.44 mm slightly under the prescribed 1.5 mm (fig.7). This beneficial difference occurs due to the convergence tolerances the program has taken into account. The maximum von Mises stress also improves, as it decreased to 31.38 MPa.

Fig. 7. Displacements distribution on the optimized rod

Table 4 shows the values of the dimensions that were modified during optimization. It can be noticed that, even if the rod's diameter had the highest absolute increase, from a relative point of view all three dimensions significantly influenced the final result.Even if the retractable rod's mass has increased after optimization, related to the initial mass of the metallic part it is with 68 % lighter (table 5). By replacing all 11 metallic rods with polymeric ones, a 3.2 kg mass reduction will be achieved, together with higher durability and corrosion resistance. Another advantage consists in an easier manufacturing process by means of injection molding. In addition, the friction coefficient can be reduced to 0.09 if using 15 % graphite filled poliketone. Graphite also increases wear resistance especially on high temperatures that can occur in operation as a result of friction between parts [12].

As it was proved, the polymeric parts have numerous advantages compared with metallic ones. Never the less, it is recommended to use specialized analysis programs during the design process, or problems like over-engineering and under engineering can occur. While first of them can lead to unnecessary costs and material usage, the later can result in part failure.

Table 4

DIMENSIONS CALCULATED AFTER THE OPTIMIZATION PROCEDURE

Dimension	Initial Value	Final Value	Difference	
			absolute	relative (%)
Diameter of Rod (mm)	14	24	10	71
Fillet Radius (mm)	2	3	1	50
Hub Thickness (mm)	4	6	2	50

Table 5

MASSIC CHARACTERISTICS OF THE OPTIMIZED PART

	Metalic Rod	Initial Polymeric Rod	Optimized Polymeric Rod
Mass (g)	430.41	55.9	136.6
Relative difference in relation with the optimized part, absolute value (%)	215	59	-

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