Method and device for dynamic modelling of rubbery materials applied to human soft tissues. Part I: determination of mechanical characteristics and dynamic model proposal

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Abstract. The paper aims to study the dynamic behaviour human soft tissues, based on the similarity noticed between the tensile stress-strain curves, for soft biological tissues and rubbery materials. Elastic materials, like rubber and steel, were tested for different types of loadings. In order to establish a dynamical model, the force-elongation dependency of the rubber wire is required. A rubber wire was loaded axially by increasing loads and the deformations up to more than 100% strains were registered. The experimental points from force-displacement plot were interpolated and the function proposed was chosen.

1. Introduction
Development of cutting edge technology and engineering focussed to new requirements imposed to working materials. For materials producers the challenges expand day by day, [1]. Time and again, the needs imposed to new materials are opposing, being dictated by the extreme conditions under which different devices must work, [2]. As a result to the large variety of imposed characteristics, new materials occurred - composite materials, metal carbides etc., [3]. Also, at the same time, researchers reconsidered classical materials, [4]. One of the most widespread materials and employed in versatile applications is beyond doubt, rubber. Without rubber, the existence of automotive industry would be unthinkable, [5]. Rubber is also met in everyday life, from sealing techniques to irrigations systems, [6]. The broad range of mechanical characteristic variations recommended rubber, for the last period, for applications in peak technologies, military industry, space engineering, [7], bioengineering, [8], medical equipment, [9]. Finally, one can say that rubber found a broad practicability as alternative for soft human tissues. Employment of rubber as replacement for soft human tissues supposes a very good knowledge of mechanical characteristics of live tissue, [10] to be substituted, finding the formula of the artificial materials with the characteristics closest to the living tissue, [11], [12] and not least, precautions that, in time, the properties of the artificial material will remain unchanged. The last constraint is especially important considering that the substitution of original tissue with an artificial one is made regularly by surgery. If the characteristics of the artificial material alter in time, obviously, the necessity of repeated surgery is obvious. As emphasised above, understanding the mechanical characteristics of rubber is particularly important. This is an extremely difficult task considering the polymeric structure of rubber. An isotropic and non-homogenous behaviour is expected, [13]. Additionally, as outlined in scientific literature, rubber can be characterised by means of rheological properties.
2. Experimental force-deformation tests

The stress-strain characteristic curve of a material subjected to a certain test offers a wealth of information. The shape of this curve depends essentially by the test type. The simplest examples presented are the traction test of a steel probe and the contact test for elastic materials.

In the case of traction test, for stresses below a definite value, proportionality between strains and stresses is observed but for the Hertzian contact, the force depends on the deformation raised to half-cube power.

Next, the elastic characteristics obtained for rubber bodies of different shapes are presented. The following situations were considered:
- Contact test between a steel ball and a rubber block
- Compression test for a rubber block
- Traction test for filiform rubber bodies

The first three tests were performed on GADALBINI QUASAR 600 equipment, [14]. The first two types of tests required the design of a special loading device. Figure 1 presents the grips of the equipment, the loading device together with the ball and rubber block.

Figure 1. Device for contact tests of a cylindrical rubber block
1 - grips; 2 - loading device; 3 - \( \phi 40 \) bearing ball; 4 - rubber block

In figure 2 there are presented the load-displacement curves for a cylindrical rubber body compressed by steel ball. The curves present similar shapes to the ones given in technical literature, [10]. One can notice the hysteresis phenomenon and the fact that there is no remnant deformation. In order to interpolate the points from the loading and unloading curves, exponential function can be used. The precision in obtaining the parameters of interpolation curves is essentially depending on the accuracy of identifying the point of contact initiations. This aspect was highlighted for metallic bodies by Oliver and Pharr, [15-16] and Prchlik, [17].

To exemplify the above considerations, in figure 2 there is presented the time variation for the loading curve of a contact between a bearing ball and a plane disc made of mild steel. It is clearly that the transition from horizontal variation to the actual loading curve is made via a transition region where it is difficult to appreciate what actually happens: the contact initiation takes place or there are deformations of the loading system. In figure 3 there are presented comparatively the time dependences of loading force with ball (1) and without ball (2). In both situations it is observed the
transition region. The different shapes of the curves in the transition regions don’t conduct to a conclusion concerning the point of contact beginning.

Figure 2. Difficulty encountered in identifying the point of contact initiation

Figure 3. Comparison between loading force variation for the cases: with ball (1) and without ball (2)

Figure 4. Compression of a rubber plate between two steel discs

Figure 5. Force-deformation dependency for the compression test of rubber plate – three different compositions

For performing the compression test, in the loading mechanism was assembled a device consisting of two steel discs and a rubber plate. The loading force variation versus deformation is presented in figure 5. The deformations of the rubber probe are in the large deformations domain.
3. Experimental traction tests for rubber string

The last test considered was of a filiform rubber probe under traction. There were considered cords made from the same type of rubber with different diameters of the cross-section: 2 mm, 2.5 mm and 3 mm. They were loaded using weights and measuring after each loading augmentation, the distance between two marks set on the unstretched wire. Figure 6 shows two curves corresponding to the traction tests performed on two cords from the same material, with the same cross-section but with different initial lengths, \( l_{01} = 0.505 m \) (1), \( l = 0.755 m \) (2).

To compare the effect of force upon the dimensions of loaded cord, the force versus strain variations were represented. For the first cord, one could notice that after surpassing 100% strain, the strain increases very much and the creep occurs. For the second rope, the forces were lower and produced strains below 100%. Interpolation points lie down on a curve having a shape similar to the curves presented by Reeves, [18], for the force-deformation variation for a human tendon.

The points from this graph were considered in finding the interpolation curve. Numerous expressions may be chosen for the interpolation curve. Assuming that the expression of the interpolation curve will be further used in structuring a dynamic model, it is aimed that the interpolation function should contain few parameters as possible but as much as necessary to accomplish a good quality interpolation. To this reason, the expression proposed by Chacon, [19], was selected for the interpolation function:

\[
f(x) = -k\left[ x f\left(2 - \tanh\left(\frac{x}{a}\right)\right) + bx^3 \right]
\]  

(1)

where \( k \), \( a \) and \( b \) are constants found from the condition of minimization of the function

\[
\phi(k,a,b) = \sum_{i=1}^{n} [f(x_i) - F_k]^2
\]

(2)

In figure 7 there are presented the experimental point from curve (2), figure 6 and the interpolation curve.

**Figure 6.** Loading curves for two cords with the same cross section but different lengths

**Figure 7.** Experimental points and the interpolation curve

From figure 6 and figure 7 it is easily observed the non-proportional relationship between forces and strains that will have immediate consequences upon the type of differential equation selected to describe the behaviour of the system containing the rubber body. The differential equation will be a nonlinear one. It is obvious that from the structure of differential equation should not be neglected the
damping factor - a consequence of internal friction from rubber string. This aspect is evidenced in the second part of the paper.

4. Conclusions
The aim of the paper is to propose a dynamical model capable to describe the dynamical behaviour of rubber bodies when employed as human soft tissues substitutes. Taking into account that the main feature required to these materials is to present physical and mechanical characteristics closer to the original tissue, the first part of the work presents the experimental results obtained on original test rigs with the purpose of plotting the force-deformation curves for diverse loading types and body models.

There are presented the characteristic curves obtained at the compression of a steel ball on a rubber block, the compression curve of a rubber plate and the traction curve of a filiform rubber body.

Comparisons with the correspondent curves presented in technical literature traced for the soft human tissues revealed that the best similarity exist for the traction curves of filiform bodies. For this type of test there were made several experiments and each time it was concluded that there is an initial region where the deformations increase more rapidly than the force, followed by a zone where the other way happens.

Proposition of a dynamical model assumes the existence of an analytical relation between force and deformation. Using for the interpolation function an expression proposed in scientific literature, a relationship between force and deformation was obtained and it will be further employed in construction of dynamical model and presented in the second part of the paper.

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