Nonlinear modeling and experimental evaluation of fluid-filled soft pads for robotic hands

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ABSTRACT. After a brief reminder about previous work, this paper addresses the dynamic characterization of fluid-filled soft pads for robotic hands.
The adopted pad specimens are constituted by a single hyper-elastic material having hardness similar to that of the human thumb. The overall pad thickness is then divided into a continuous skin layer and an internal layer having communicating voids which are hermetically sealed and filled with a viscous fluid. Despite a more complicated design, it has been proven [1-3] that the pads present enhanced compliance and damping properties, a lower thickness and a higher surface hardness when compared to previously published solutions.
In addition, a quasi-linear model, frequently used to describe the behavior of soft biological tissues can be applied in order to predict and control the pad interaction with the environment during grasping and manipulation tasks. In particular, the experimental tests necessary to evaluate the parameters which determine the pad dynamic response are described and discussed in detail.

KEYWORDS. Soft fingers, viscoelasticity, quasi-linear model.

INTRODUCTION

The many benefits of a surface compliance for robotic devices which must safely interact with an unknown environment are well known and widely discussed in the literature [4-6]. An outstanding case are anthropomorphic robotic hands which try to reproduce the shape and the capabilities of the human hand. In such a case, the presence of a viscoelastic pad can enhance the *stability* and the *sustainability* of the grasp during grasping/manipulation tasks [6] and it is beneficiary in terms of *safety* and *acceptance* [1-3,7] of the hand in case of human-robot interaction.
In terms of soft cover realization, the majority of pads for robotic hands studied so far were made by viscoelastic polymeric solids homogenously shaped over an internal rigid core mimicking the bone or the robotic finger inner rigid structure [6,8,9]. In such a case, the contact between the cover and the object to be manipulated has been defined as *viscoelastic contact* [6] and includes a Time-Dependent (TD) response, due to relaxation or creep phenomena [10], in addition to a Time-Independent (TI), non linear, elastic response.
Concerning the pad design and its viscoelastic properties, it has been recently shown that better behaved covers can be achieved by means of fluid-filled structures [1] with *Differentiated Layer Design* (DLD) [2,3]. The concept of DLD consists in the adoption of a single solid material dividing the overall thickness of the pad into layers with different structural design (e.g. a continuous skin layer coupled with an internal layer with voids). The internal layer voids (which are purposely shaped so as to obtain a predefined compliance) are hermetically sealed and filled with an incompressible viscous fluid. Fig. 1 shows a DLD soft pad with fluid-filled structure mounted on a rigid core (3D model and pad prototype).

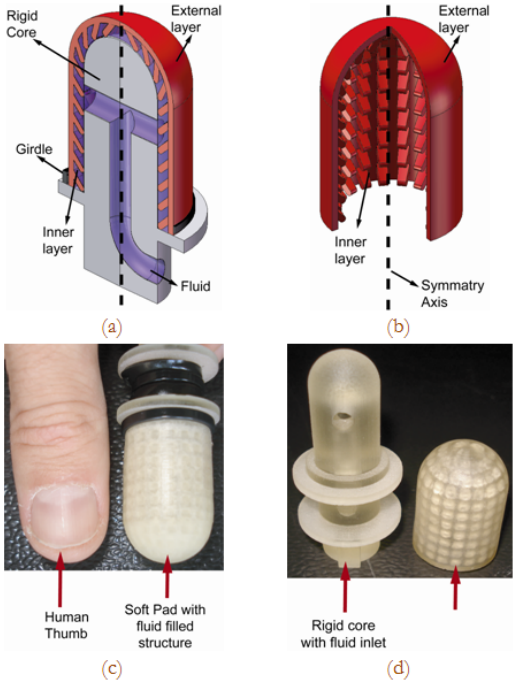


Figure 1: Fluid-filled DLD soft Pad. 3D model (a), longitudinal cross section (b). Specimen comparison with human thumb dimensions (c), rigid core with fluid inlet (d). See [1] for details.

Despite a more complicated design, these fluid-filled structures possess enhanced compliance and damping properties, a lower thickness and an higher surface hardness when compared to the mentioned homogenous solids [1].
Concerning pads modeling and control, much work has been done by Biaggiotti et al. [9] and by Tiezzi et al. [10] which exploited the well known Fung's "*quasi-linear*" model [11] to capture the dynamic behavior of an homogenous viscoelastic layer pressed against a rigid flat surface. The Fung viscoelastic model (see Sec. 2) postulates an elastic non-linear TI response set apart from the TD response and it has been mainly employed to model soft biological tissues such as the human ligaments [12] or the fingertip pulp when subjected to indentation [13] or during dynamic tapping tasks [14].
Aim of this paper is to validate, by means of experiments, the applicability of the Fung's hypothesis when predicting the dynamic behavior of fluid-filled soft structures (Fig. 1). An efficient numerical technique, firstly proposed in [12], is applied in order to assess the parameters which determine the pad dynamic response during indentation.

THE "QUASI-LINEAR" VISCOELASTIC MODEL

Theoretical Background

Many polymeric solids exhibit a stress/strain behavior which is significantly influenced by the rate of application of the external loads or displacements. Citing [9] and considering a simple one-dimensional model, the overall force response to a step change in displacement δ_0 (or, dually, the displacement response to a step change in the external load F_0) depends on time (t) as well as on the value of the step itself, i.e.

$$F(t) = \Psi(\delta_0, t) \tag{1}$$

$$\delta(t) = \Phi(F_0, t) \tag{2}$$

The functions Ψ (*relaxation function*) and Φ (*creep compliance*) depend, respectively, on the imposed displacement δ or force F as well as on the time t.
Creep and relaxation are two aspects of the same viscoelastic behavior and can be related [15]. In order to compare to previously published results [9-10] the following analysis studies the relaxation phenomenon following an imposed displacement. Nevertheless the same arguments hold if a force is applied and creep phenomena are investigated. In order to simplify the analysis, Fung [11] formulated the following form for the *relaxation function*:

$$\Psi(\delta,t) = F^{(e)}(\delta)\cdot g(t) \text{ with } g(0)=1 \tag{3}$$

where $F^{(e)}(\delta)$ is the *elastic response*, that is the amplitude of the force generated instantaneously by a displacement δ , while $g(t)$, called *reduced relaxation function*, describes the time-dependant behavior of the material. Considering the Fung's hypothesis, the force produced by an infinitesimal displacement $d\delta(\tau)$, superimposed in a state of displacement δ at an instant of time τ, is, for $t > \tau$

$$dF(t) = \frac{\partial\Psi[\delta(\tau),t-\tau]}{\partial\delta}d\delta(\tau) \tag{4}$$

and, considering the Fung's hypothesis, expressed in (3), one achieves

$$dF(t) = g(t-\tau)\frac{dF^{(e)}[\delta(\tau)]}{d\delta}d\delta(\tau) \tag{5}$$

By applying a modified superposition principle, discussed in [11], [15], the total force at the instant t is the sum of the contribution of all the past changes, i.e.

$$F(t) = \int_0^t g(t-\tau)\, K^{(e)}[\delta(\tau)]\dot{\delta}(\tau)d\tau \tag{6}$$

where the term $K^{(e)}(\delta) = \frac{dF^{(e)}[\delta]}{d\delta}$ is the elastic stiffness and $\dot{\delta}(\tau)$ is the rate of displacement. The lower limit of the integral is zero (and not $-\infty$) assuming that the contact occurs at time $t=0$ and $F^{(e)}=0, \delta=0$ for $t<0$.
The reduced relaxation function $g(t)$ is a decreasing and continuous function of time, normalized to 1 at $t=0$. A quite general form for $g(t)$ has been proposed in [10]. However, utilizing the reduced relaxation function proposed by Fung can be quite complicated. A simpler yet accurate form is therefore preferred [16] which is composed by a linear combination of exponential functions (with the coefficient c_i depending on the material in homogenous structures)

$$g(t) = \sum_{i=0}^{r} c_i e^{-v_i t} \text{ with } \sum_{i=0}^{r} c_i = 1 \tag{7}$$

whose exponents v_i identify the rate of the relaxation phenomena. Note that $v_0 = 0$. The number r and the value of such parameters depend on the behavior of the system under analysis.
The nonlinear elastic response $F^{(e)}(\delta)$ can be approximated by the force response in a loading experiment with a sufficiently high rate of displacement. The force $F^{(e)}(\delta)$ differs from the steady state response of the material for the constant $c_0$and it can be modeled as:

$$F^{(e)}(\delta) = \frac{m}{b}(e^{b\delta}-1) \tag{8}$$

In the following, the analysis will be limited to hemispherical pads pressed against a rigid flat surface (platen).

Numerical fitting of the model constants

The values for the constants m, b, v_i, c_i can be assessed by imposing a "ramp-hold" displacement history to the pad specimens (Fig. 2) and measuring the resultant compressive force.

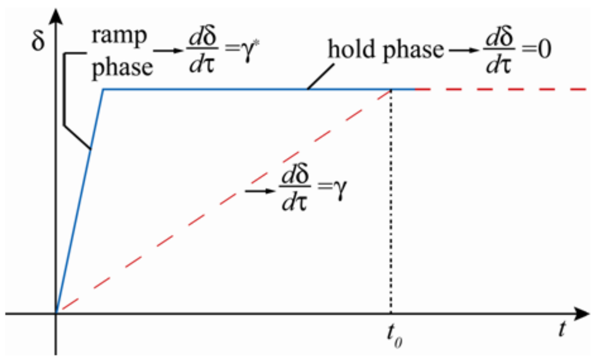


Figure 2: Trajectory of displacement used to determine the model constants: "ramp-hold" test

In particular, the fitting procedure proposed in [11] is composed of two steps:

- ✓ At first the specimens are pressed against a rigid surface by imposing a given displacement δ at increasing speed $\dot{\delta}$. A sufficiently high $\dot{\delta} = \gamma^*$ is determined upon which the TD effects are negligible, (i.e. for $\dot{\delta} \to \infty$ the response of the material is similar to that to an ideal step). This force-displacement profile is taken as a good approximation of the purely elastic response $F^{(e)}$ and can be used to determine m, b.
- ✓ Once γ^* , m, b are known, the values for v_i, c_i are determined analyzing the force response to the "hold phase" of the imposed trajectories.

Nevertheless, the application of very high displacement rates can be problematic as long as it can induce shock waves (especially when dealing with fluid-filled structures) and inertial forces which influence the force measurement. Therefore, the fitting technique addressed in [12] is preferred. Note that, if the reduced relaxation function expressed by Eq. (3) is used, Eq. (6) can be easily solved concerning both the ramp phase and the hold phase of the experimental test. Let us consider a constant velocity indentation of the specimen starting at $t = 0$ with the pad barely touching the platen (uninflected configuration). From $t = 0$ to $t = t_0$, there is a constant linear increase in displacement with slope γ (velocity of indentation). The total displacement at any time during the ramp is simply $\delta = \gamma t$. Thus, for this time frame (assuming the *reduced relaxation function* of Eq.(7)), the total force $F_1(t)$ for $0 \leq t \leq t_0$ is given by:

$$F_1(t) = \int_0^t \left(\sum_{i=0}^{r} c_i e^{-v_i t} \right) \gamma m\, e^{b\gamma t} d\tau = \sum_{i=0}^{r} \frac{m\gamma c_i (e^{b\gamma t} - e^{-v_i t})}{b\gamma + v_i} \tag{3}$$

On the other hand, the force response from t_0 to the end of the experiment includes the force history up to t_0 plus the force history from t_0 onward. However, since the displacement rate from t_0 onward is zero, the total force $F_2(t)$ for $t > t_0$ is given by:

$$F_2(t) = \int_0^{t_0} \left(\sum_{i=0}^{r} c_i e^{-v_i t} \right) \gamma m\, e^{b\gamma t} d\tau == \sum_{i=0}^{r} \frac{m\gamma c_i (e^{-v_i t} (e^{(b\gamma + v_i) t_0} - 1))}{b\gamma + v_i} \tag{3}$$

The model parameters are then determined by minimizing the following objective function:

$$\underset{m, b, v_i, c_i}{Min} \int_0^{t_0} \left(F_{1exp}(t) - F_{1mod}(t) \right)^2 dt + \int_{t_0}^{\infty} \left(F_{2exp}(t) - F_{2mod}(t) \right)^2 dt \tag{3}$$

Where F_{1exp} and F_{2exp} are the forces of the real system for $0 \leq t \leq t_0$ and for $t > t_0$ respectively, whereas F_{1mod} and F_{2mod} are the modeled forces for $0 \leq t \leq t_0$ and for $t > t_0$ respectively. The abovementioned procedure allows to reduce the maximum indentation to $\gamma < \gamma^*$ (dashed line in Fig. 2). In the following, the parameter r will be chosen such that r =2. A "ramp-hold" test having γ =20mm/s is used for determining the system constants m, b, v_i, c_i.

Experiments and Numerical Fitting

The pad specimens are composed of an external uniform layer with hemispherical geometry and an intermediate layer with fluid-filled voids. Similarly to the results reported in [18], the pad outer diameter is 20mm whereas the pad overall thickness is 3mm. The inner layer voids are hermetically sealed by means of girdles (Fig. 1) and filled with an incompressible fluid so as to modify the TD phenomena (such as creep, stress relaxation, recovery time and energy dissipation). The Pad solid structure is made of *Tango Plus Fullcure 930* (hardness 27 Shore A) which is a polymeric resin used for Rapid Prototyping. Beside the use of simple DLD pad hermetically sealed (Pad A), two different fluid-filled pads are tested:

- ✓ Pad C: DLD pad filled with lubricant oil (viscosity 0.03$Nsec/m^2$ at 20°).
- ✓ Pad D: DLD pad filled with glycerin (viscosity 1.5$Nsec/m^2$ at 20°).

For each fluid, tests have been performed analyzing contact on the hemispherical end of the pad pressed against a rigid flat surface. The adopted experimental set up is visible in Fig. 5 and it is composed of a linear motor (Linmot P01-23x80) equipped with an high resolution position sensors (1μm being the maximum resolution), whose slider is directly connected with a load cell which supports a 35mm x 35mm flat rigid platen weighting 10g. A general purpose DSP board is used to implement a basic position controller (with a sampling time of 1ms). In this way, proper trajectories are applied to the platen, that is pressed against the soft pad imposing a controlled deformation. Through the load cell (characterized by a structural stiffness of 242.000N/mm, an overall weight of 11g, and accuracy of 0.1N) the normal component of the contact force is continuously monitored. The maximum acceleration imposed to the platen in all the experiments is about 1000mm/s^2 resulting in a maximum inertial force of 0.01N (reasonably neglecting the inertial effect due to the pad deformation). Inertial forces, which are not captured by the load-cell, are therefore disregarded.

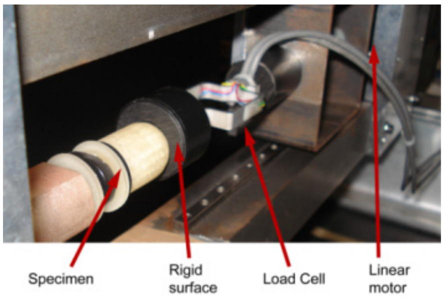


Figure 3: A general view of the experimental set-up.

The experimental analysis is performed by compressing the pad to a displacement of 1.6 mm (*forward displacement*) using six different rates of loading (0.1, 1, 10, 20, 30, and 100mm/s), as demonstrated in Fig. 4 (results concerning 20, 30mm/s are omitted for clarity). The maximum displacement of the pad (1.6mm) is held constant for approximately 30s, allowing the response forces of the fingertip to stabilize. The platen displacement is then reduced to 0.80mm (*backward displacement*) at a speed of 1.00mm/s, and the displacement (0.80mm) is held constant for another 30s.
Figure 5(a) shows experimental and calculated results for the DLD Pad filled with lubricant oil (Pad B) whereas Fig. 5(b) shows experimental and calculated results for the DLD Pad filled with glycerin (Pad C). Results concerning 10, 20, 100mm/s are omitted for clarity). It can be seen that the Fung's model is capable of capturing the one-dimensional viscoelastic behavior of the fluid-filled pads proving that, even if the design can become more complicated when compared to a uniform pad, the modeling procedure (used in grasp and manipulation control algorithm [13]) could remain unaltered. Numerical results for the model constants concerning Pads A, B, C are reported in Tab. 1.

PAD	m	b	c_0	c_1	c_2	ν_1	ν_2
A	0.518	0.577	0.3076	0.6200	0.0724	6.2350	0.1750
B	0.3400	1.1650	0.2955	0.6300	0.0745	6.2150	0.1400
C	0.9750	0.5190	0.3290	0.6300	0.0410	6.2150	0.1400

Table 1: Coefficient values of Eq. (6) for pads a,b,c.

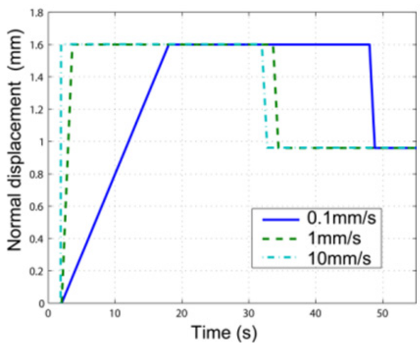
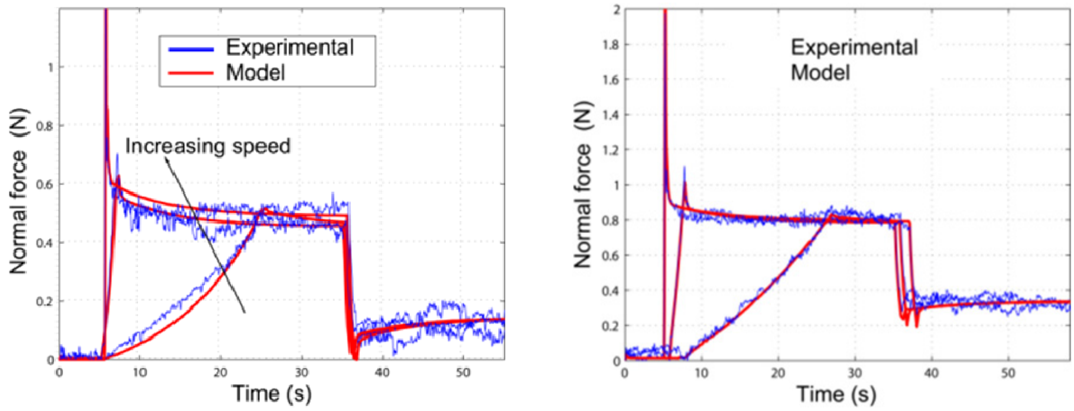


Figure 4: The prescribed displacement histories of the compression platen.

Conclusions

In this paper, the dynamic model for fluid-filled soft pad has been discussed. Similarly to what happens for soft covers made of homogeneous viscoelastic solids, the model can be efficiently applied for predicting the force response of the specimens as a function of displacement and time. A "ramp-hold" test has been carried out in order to assess the constants which determine the system behavior. The model is then validated by predicting the pad response to a forward displacement at different velocities followed by a backward displacement. Finally, the numerical results concerning two different fluid-filled soft pads have been presented.



(a) (b)

Figure 5: Force responses as a function of time for Pad D (a) and Pad E (b) subjected to the prescribed displacement histories as shown in Fig. 6 at different velocities (0.1, 1 mm/s, 30 mm/s respectively). Experimental results and model prediction

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