MODELLING AND IDENTIFICATION OF SOFT PADS FOR ROBOTIC FINGERS

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Introduction. In this work the dynamic contact of a hemispherical indenter covered by a thick viscoelastic layer and pressed against a flat rigid surface is modeled. The goal is to investigate the dynamic behavior of robotic fingertips composed by an inner rigid structure covered by a soft layer, mimicking the human biological model. A quasi-linear model, frequently used to describe the behavior of soft and pulpy biological tissues, is adopted in order to achieve a compromise between the simplicity of classical linear models and the difficulty of nonlinear approaches. Two different materials (a polyurethane gel and a silicon rubber) have been tested experimentally.

The quasi-linear viscoelastic model

Many materials (e.g. polymers) exhibit hysteresis, relaxation and creep phenomena when they are deformed and loaded by external forces. Such a behavior is defined viscoelastic since the elastic response is affected by time-dependent phenomena that are characteristic of viscous materials [1]. In the general case the material behaves nonlinearly and the relation between forces \( F \), displacements \( \delta \) and time \( t \) follows equations of the form:

\[
F = \Psi(\delta, t)
\]  

(1)

The function \( \Psi \) is named relaxation function. Since the modeling of viscoelasticity usually leads to extremely complex results, in order to simplify the analysis and to achieve models more suitable for practical purposes, some additional hypotheses are necessary.

Fung [2] formulated a significant hypothesis assuming that the relaxation function has the form:

\[
\Psi(\delta, t) = F^{(e)}(\delta) \cdot g(t) \text{ with } g(0)=1
\]  

(2)

where \( F^{(e)}(\delta) \) is the elastic response, which is the amplitude of the force instantaneously generated by a displacement \( \delta \), while \( g(t) \), called reduced relaxation function, describes the time-dependent behavior of the material. The force produced by an infinitesimal displacement \( d\delta(\tau) \) superposed in a state of displacement \( \delta \) at an instant of time \( \tau \) is, for \( t>\tau \),

\[
dF(t) = g(t-\tau) \cdot \frac{\partial F^{(e)}[\delta(\tau)]}{\partial \delta} \cdot d\delta(\tau)
\]  

(3)

By applying a modified superposition principle, discussed in [2], [3], the total force at the instant \( t \) is the sum of contribution of all the past changes, i.e.

\[
F(t) = \int_0^t g(t-\tau) \cdot \frac{\partial F^{(e)}[\delta(\tau)]}{\partial \delta} \cdot \frac{\partial \delta(\tau)}{\partial \tau} \cdot d\tau
\]  

(4)

The relaxation function \( g(t) \) is a decreasing continuous function of the time, normalized to 1 at \( t=0 \). It is composed by a linear combination (with the coefficient \( c_i \) depending on the material) of exponential functions, whose exponents \( \nu_i \) identify the rate of the relaxation phenomena, i.e.

\[
g(t) = \sum_{i=0}^{\infty} c_i \cdot e^{-\nu_i t} \text{ with } \sum_{i=0}^{\infty} c_i = 1
\]  

(5)

The parameters \( \nu_i \) (\( i=1...r \)) depend on the behavior of the system under analysis, while \( \nu_0 = 0 \).

The elastic response \( F^{(e)} \) can be approximated by the force response in a loading experiment with a sufficiently high rate of displacement, without inducing shock waves. The nonlinear elastic response can be modeled through different analytical expressions. Two are the most important models of the elastic stiffness adopted in literature:

\[
K^{(e)} = m \cdot e^{b \cdot \delta}
\]  

(6)

\[
K^{(e)} = p \cdot \delta^q
\]  

(7)

where (\( m, b) \) and (\( p, q) \) are parameters which depend on the material and the geometry taken into account.
Experimental equipment and fingertip specimen
In order to test some soft pads and to find a proper model, a simple setup has been implemented. It is based on a linear motor whose slider is directly connected with a load cell, which supports the fingertip specimen, as shown in Fig. 1.

![Linear motor, Load cell, Soft finger specimen, Rigid wall](image)

Figure 1.

The motor is equipped with a high-resolution position sensor and through the load cell the normal component of the contact force is continuously monitored.

The tests are conducted on simplified fingertips (see Fig. 2), which have a hemispherical geometry with an outer diameter of 20 mm and a constant thickness of the soft layer (equal to 6 mm), bounded to the rigid inner structure.

![Figure 2. Simplified fingertip](image)

The experimental analysis is performed on two different materials, characterized by considerably different viscoelastic behaviors:

- Silicon rubber (hardness 20 Shore 00);
- Polyurethane gel (hardness 40 Shore 00).

Method, experimental results and model fitting
The experimental analysis is performed following three subsequent phases [4]. The first two phases are executed to identify the parameters of the system (i.e. \((b, m)\) or \((p, q)\) and \(c_i, \nu_i\)); the third is carried out to validate the obtained model.

1. The force response of the fingertip specimen to deformations imposed with different velocities is examined in order to determine the velocity above which rate-dependent effects are negligible.
2. The system identification is carried out applying a trajectory composed by two parts: a fast rising ramp followed by a constant position hold phase. The goal is to identify the elastic instantaneous response \(F^{(e)}\) through the fast ramp, and the time-dependent effects (i.e. \(c_i, \nu_i\)) in the hold phase.
3. The model is validated by means of a sequence of steps with different amplitude.

Figure 3 shows the force response of the polyurethane rubber due to a fast ramp (30 mm/s) followed by a hold position phase, while Fig. 4 shows the experimental results and those predicted by the model for the polyurethane rubber when a sequence of steps is applied. Obviously, the model loses its validity when the contact stops.

![Figure 3. Force response of polyurethane rubber](image)

![Figure 4. Experimental results and model fitting](image)

Conclusions
In this work a dynamic model for viscoelastic pads is developed. The model can be used to characterize the behavior of materials, which can be used to cover bio-inspired robotic hands. On the other hand, the model is suitable for simulation purposes, in order to reproduce the response of a compliant pads when the contact between the robot and the environment occurs.

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Reference