Mechanical characterization and identification of a dielectric elastomer

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Résumé :

Les structures mécaniques sont soumises à des vibrations liées à l'environnement ambiant ou à des pressions acoustiques. Celles-ci penvent être utilisées pour produire de l'énergie à l'aide de transducteurs convertissant les charges mécaniques en polarisation électrique. L'utilisation de matériaux intelligents tels que l'EAP (polymère électroactif) pour récupérer l'énergie de ces vibrations mécaniques est un concept récent et prometteur. Cette étude porte sur la caractérisation et l'identification des propriétés mécaniques d'un matériau élastomère (3M® VHB 4910) pouvant être fonctionnalisé, par exemple en un matériau EAP pour le contrôle de l'énergie acoustique.

Des essais mécaniques ont été effectués sur une machine d'essai de traction équipée d'une chambre environnementale permettant de contrôler la température et l'humidité. Les essais de traction ont été effectués avec une vitesse de déformation imposée pour différentes températures. Les mesures force-déplacement obtenues ont été filtrées en utilisant une méthode de moyenne glissante.

La réponse force-déplacement met en évidence un stockage d'énergie dans le matériau et une dépendance à la température. En supposant l'incompressibilité du matériau, trois modèles hyperélastiques ont été considérés : le modèle néo-hookien à un paramètre, le modèle de Mooney-Rivlin à deux paramètres et le modèle d'Ogden à deux paramètres. Chaque jeu de paramètres du matériau a été identifié à l'aide d'une méthode inverse non linéaire. Il a été observé, d'une part que le modèle néo-hookien ne correspond pas bien aux données expérimentales, et d'autre part que le modèle de Mooney-Rivlin est plus précis que celui d'Ogden. Ainsi, il semble que le modèle de Mooney-Rivlin constitue le meilleur compromis entre complexité et précision. La relation entre le module de cisaillement initial et la température a été approximée par un relation linéaire avec une faible erreur résiduelle.

Abstract :

Mechanical structures are subjected to ambient vibrations or acoustic pressures which can be used to produce energy using adequate transducers that convert mechanical loadings into electrical polarization. The use of smart materials such as EAP (electro-active polymer) to harvest energy from the mechanical vibrations of the surrounding environment is a recent and promising concept. This study focuses on the characterization and identification of mechanical properties for an elastomer material (3M® VHB 4910) which can be functionalized such as an EAP material for acoustic energy control.

Mechanical tests have been carried out using tensile testing machine equipped with a thermo-conditioning *device to control the environmental conditions (temperature and humidity). Tensile test have been performed with an imposed loading–unloading strain rate for various temperatures. The measured force–displacement data have been filtered by moving mean.*

The force–displacement response exhibits an energy storage within the material and a dependence on temperature. Assuming incompressibility, three hyperelastic models have been considered : the Neo-Hookean model with one parameter, the Mooney-Rivlin model with two parameters and the Ogden model with two parameters. Each set of material parameters has been identified by using a non-linear inverse method based on non-linear least squares. It has been observed that, not only the Neo-Hookean model does not fit well with experimental data, , but also the Mooney-Rivlin model is more precise than the Ogden model. Thus, it has been found that the Mooney-Rivlin model is the best compromise between complexity and suitability. The relationship between initial shear modulus and temperature has been approximated by a linear relationship with a sufficiently small residual error.

Keywords : Elastomer – Mechanical characterization – Thermo-mechanical effect – Parameters identification

1 Introduction

Mechanical structures are subjected to ambient vibrations or acoustic pressures which can be used to produce energy using adequate transducers that convert mechanical stresses into electrical polarization. The energy produced in these cases can be stored and used in non-energy-intensive applications for which the autonomy is a priority, irrespective of the external conditions under which these structures are located. This approach to the production of clean and secure energy (endurable, wireless) now occupies a prominent place in many applications. It is very well adapted to intelligent systems of small sizes such as sensor networks or embedded systems, or mobile phones for various applications for example, surveillance, diagnosis and control in a transportation facility, aeronautics, biomedical, the environment, etc. In addition, the use of intelligent materials in the recovery of energy from the mechanical vibrations of the surrounding environment is a recent and promising concept. For this, electro-active polymers (PEA) are materials that have the ability to change shape and size when a certain voltage or currant intensity is applied to them. The use of these polymers has recently emerged to take advantage of their mechanical behavior and especially the use of dielectric elastomer (DGEs) as an energy harvesting device can dramatically improve transduction performance in storage energy density and non-linear properties (large displacements and large deformations).

In this multi-physics and multidisciplinary project, we are interested in the characterizing and the modeling of a material marketed by 3M company under the name of "VHB 4910" (see Ref. [1]) for different temperatures.

2 Experiments

2.1 Specimen preparation

The 3M VHB 4910 is in the form of an adhesive tape with a thickness of 1 mm and a width of 5 cm. The gelatinous aspect of this elastomer leads to some difficulties during the realization of the tensile tests, especially in the cutting of the samples. It is very easy to impose a pre-tension within the materials if we cut it with a cutter which could trigger the non-repeatability of test results. The chosen solution is to cut the sample along its width direction instead of its length direction. The sample dimensions are finally fixed at a length of 40 mm, a width of 50 cm and a thickness of 2 mm (consisting of the superposition of two adhesive tape layers). Figure 1 shows some samples which have been tested.

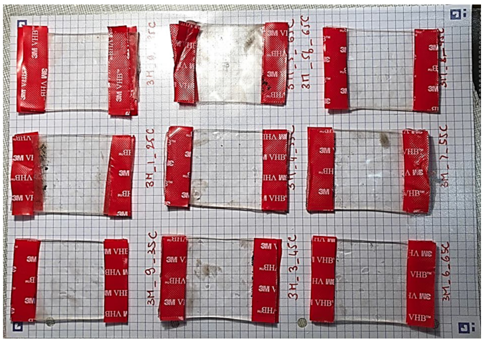


FIGURE 1 – Examples of tested samples.

2.2 Experimental set-up

A universal testing machine (MTS Criterion ® : Model 45 with 'MTSS test suite' as the output software) is used for characterizing the mechanical behavior of 3M VHB 4910 at different temperatures. All the tensile tests has been performed at a imposed strain rate of $\dot{\varepsilon} = 0.125 \text{ s}^{-1}$. The machine is equipped with a thermo-conditioning device to control the environmental condition which provides a stable temperature and humidity for the test. A temperature series of $[25, 35, 45, 55, 65]$ °C with a humidity rate of 50 % has been chosen as the test environment conditions. Two tensile tests have been carried out for each temperature. It should be pointed out that tensile tests of 3M VHB 4910 have been previously studied at room temperature in Ref. [2].

2.3 Experimental processing

The tensile tests have been done by the following steps : (1) Prepare the sample carefully. (2) Prepare the input conditions (applied displacement) within the computer software. (3) Put the sample on the load cell, and tighten the crosshead properly with a wrench while keeping the crosshead parallel to avoid twisting. (4) Close the thermo-conditioning device and configure the tested temperature, wait until the environmental conditions stabilize. (5) Initialize the measured force to zero, launch the test, stop when the measured force returns to zero. Then Save the test result. (6) Open the thermo-conditioning device and remove the sample (7) Reinitialize the position of crosshead for the next test.

3 Hyperelastic modelling

A hyperelastic material is defined by an non-linear elastic behaviour for which the stress–strain relationship derives from a strain-energy density function W. For isotropic material, the strain-energy function depends upon, either the principal invariants (I_1, I_2, I_3) of the Cauchy-Green tensors, or the principal stretches (λ_1, λ_2, λ_3) :

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \; ; \quad I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2 \; ; \quad I_3 = \lambda_1^2\lambda_2^2\lambda_3^2$$

If the hyperelastic material is also incompressible, then $I_3 = 1$.

3.1 Selected models for incompressible materials

Three strain-energy density functions, namely Neo-Hookean, Mooney-Rivlin and Ogden have been previously used in Ref. [2] for describing the mechanical behaviour of VHB 4910 elastomer at room temperature. For a complete review on hyperelastic materials, see Ref. [3].

The Neo-Hookean strain-energy potential (hereinafter called 'NH model') is given by :

$$W_{\mathrm{NH}}(I_1) = \frac{\mu}{2}(I_1 - 3) \tag{1}$$

where the material constant μ is the initial shear modulus.

The strain-energy function for 2-parameter Mooney-Rivlin model (further referred to as 'MR model') is defined by :

$$W_{\mathrm{MR}}(I_1, I_2) = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \tag{2}$$

where C_{10} and C_{01} are material constants. The initial shear modulus is given by $\mu = 2(C_{10} + C_{01})$.

The strain-energy function proposed by Ogden has the general form :

$$W_{\mathrm{Ogden}}(\lambda_1, \lambda_2, \lambda_3) = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}(\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3) \tag{3}$$

where the material constants N, μ_i, α_i $(i = 1, 2, \cdots, N)$ are related to the initial shear modulus by : $\mu = \frac{1}{2}\sum_{i=0}^{N} \mu_i\, \alpha_i$.

In this paper, the N-parameter is fixed to 1, so that we consider the Ogden model with 2 parameters (μ_1 and α_1).

3.2 Uniaxial tension tests for incompressible materials

It is assumed that the 3M VHB 4910 polymer has a mechanical behaviour similar to isotopic incompressible hyperelastic materials, which can be described by the NH, MR and Ogden models. The material parameters of these models are identified by uniaxial tension tests.

In case of uniaxial tension, the principal stretch along the loading direction is $\lambda_1 = \lambda$. The incompressibility condition implies that $\lambda_2 = \lambda_3 = \lambda^{-1/2}$. The strain principal invariants are defined by :

$$I_1 = \lambda^2 + 2\,\lambda^{-1}\ ; \quad I_2 = 2\,\lambda + \lambda^{-2}\ ; \quad I_3 = 1$$

The first Piola-Kirchoff stress tensor $\mathbf{P}$ (also denoted engineering or nominal stress tensor) is then given by : $\mathbf{P} = P\,\mathbf{e}_1 \otimes \mathbf{e}_1$, where P is the unique component of $\mathbf{P}$, the symbol $\otimes$ stands for the tensor product and $\mathbf{e}_1$ is the unit basis vector along the loading direction.

In the framework of a uniaxial tension mode for isotropic incompressible hyperelastic materials, the stress component P for the successive NH, MR and Ogden models is given by :

$$P_{\mathrm{NH}} = \mu\left(\lambda - \lambda^{-2}\right);\ P_{\mathrm{MR}} = 2\left(1 - \lambda^{-3}\right)(\lambda C_{10} + C_{01});\ P_{\mathrm{Ogden}} = \mu_1\left(\lambda^{\alpha_1 - 1} - \lambda^{-\frac{\alpha_1}{2} - 1}\right) \tag{4}$$

4 Results and discussion

4.1 Experimental results

Experimental force–displacement curves do not follow the same trajectory during loading and unloading, it is an indicator that shows the existence of energy storage within the material or the existence of structural damping. Figure 2 illustrates experimental curves in terms of the first Piola-Kirchoff stress P (engineering stress) versus stretch ratio λ after filtering by moving mean for various temperatures. First, it is observed that temperature has an influence on the mechanical behaviour of 3M VHB 4910 material. Second, this figure shows that the repeatability of test results is quite good, except for the tests with temperature of 55 °C, for which discrepancies between the two tests occur at low and high stretches.

In the following of this paper, we will consider only the first test for each temperature (see Figure 2) to perform the parameter identification of material behaviour.

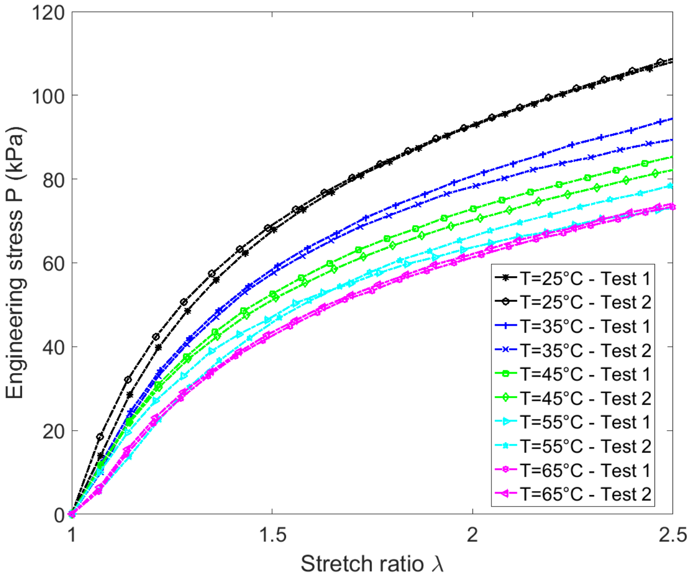


FIGURE 2 – Experimental data in terms of engineering stress versus stretch ratio after filter process.

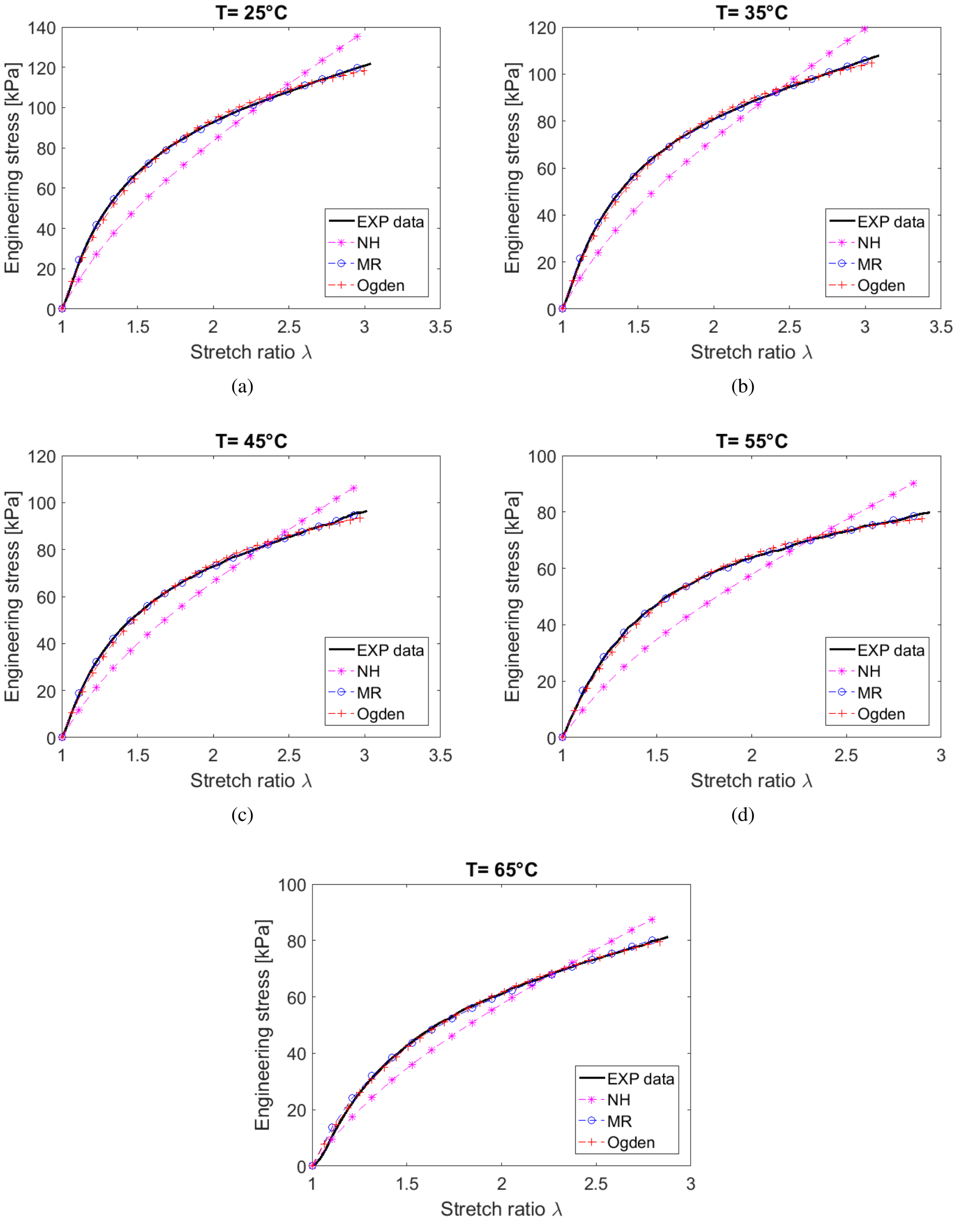
4.2 Parameter identification of hyperelastic models

Three hyper-elastic models defined by Equations (4) have been used for simulating the uniaxial tensile tests. Non-linear least squares method based on Levenberg–Marquardt algorithm has been performed in MATLAB® (function 'lsqnonlin') to minimize the discrepancy between experimental data and model results. This optimization process extracts the material parameters for the best fit between the test data and the considered model.

The identified parameters and residual sums of squares (RSS) are presented on Table 1. The residual sum of squares (RSS) is defined by :

$$\mathrm{RSS} = \sum_{i=1}^{n} \left(P_i^{\mathrm{data}} - P_i^{\mathrm{model}} \right)^2 \tag{5}$$

where P_i^{data} are the experimental data stresses, P_i^{model} the modelled data stresses, and n is the number of data points. A perfect fit would yield a small RSS.



(a) (b) (c) (d) (e)

Figure 3 – Stress–stretch curves for various hyperelastic models and temperatures after optimization. (a) : $T = 25$ °C, (b) : $T = 35$ °C, (c) : $T = 45$ °C, (d) : $T = 55$ °C and (e) : $T = 65$ °C.

Figure 3 shows the parameter identification results in terms of stress–stretch curves with temperatures of 25 °C to 65 °C. The results from Table 1 and Figure 3 show that : (1) Whatever the test temperature, the Neo-Hookean model is not capable to represent the non-linear mechanical behavior of VHB 4910 elastomer. (2) Regardless of test temperature, the Mooney-Rivlin and two-parameter Ogden models can capture the general behaviour of the stress–stretch curves. (3) By considering RSS values, the Mooney-

	NH		MR				Ogden			
T [°C]	μ [kPa]	RSS [kPa^2]	C_{10} [kPa]	C_{01} [kPa]	μ [kPa]	RSS [kPa^2]	μ_1 [kPa]	α_1 [$-$]	μ [kPa]	RSS [kPa^2]
25	47.7653	12300.	9.8883	33.0891	85.9548	29.75	141.9725	1.0208	72.4628	221.6
35	41.3455	9010.7	9.0705	27.8029	73.7468	27.5	115.5615	1.0742	62.0681	152.5
45	37.8530	6809.3	8.3316	24.8727	66.4086	11.5	105.1759	1.0683	56.1797	144.5
55	33.0365	6572.7	5.5927	25.1361	61.4576	15.8	122.4686	0.8500	52.0492	83.5
65	32.8303	2745.2	9.1798	16.3530	51.0656	110.5	70.5793	1.2598	44.4579	53.0

TABLE 1 – Results of parameters identification for various models and temperatures.

Rivlin model is more precise than the two-parameter Ogden model except for the temperature of 65 °C.

4.3 Temperature influence on initial shear modulus

The initial shear moduli on Table 1 using MR and Ogden models have been calculated according to equations presented in Section 3.1. Figure 4 shows that the initial shear modulus decreases with increasing temperature whatever the used model. In addition, a relatively good fitting is obtained by using a linear relationship between initial shear modulus and temperature.

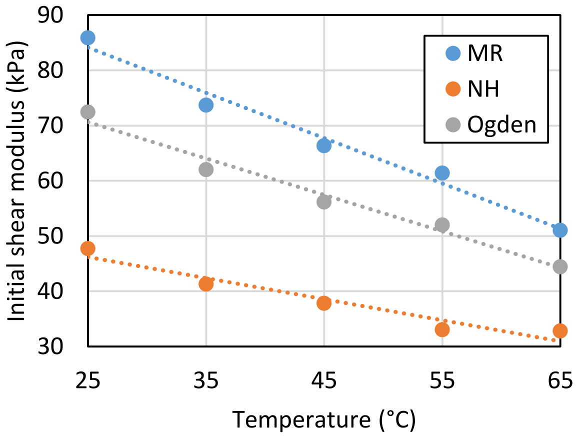


FIGURE 4 – Evolution of shear modulus versus temperature. Dotted lines are linear regressions with a coefficient of determination R^2 equal to 0.9324 for NH, 0.9802 for MR and 0.9769 for Ogden.

5 Conclusion

The main objective of this paper was to perform a parameters identification of material properties for a dielectric elastomer named VHB 4930 used as a vibration-based acoustic energy harvester. According to a previous research study [2], three hyperelastic material models have been considered to describe the mechanical behaviour using strain-energy functions for rubber-like materials.

Mechanical tests have been carried out using tensile testing machine with stable thermo-environment conditions. The test manipulation was also presented. A series of force–displacement responses have been measured and filtered to identify the model parameters according to each model. A comparison of model performance between those models has been realized. The comparison analysis has shown that : (1) The Neo-Hookean model does not fit well the experimental data. (2) The Mooney-Rivlin model is more precise than the two-parameter Ogden model except for high temperature. (3) Material damping has been observed which means the energy dispersion should not be neglected in dynamic analysis. By comparing experimental data with theoretical models, it has been noticed that the initial shear modulus is linearly dependent on temperature in the range of studied temperature. In this paper, we have studied three hyperelastic models and the Mooney-Rivlin model has been chosen as the material model to describe the material behavior for energy harvesting applications.

Références

[1] 3M Industrial Adhesives and Tapes Division, 3M VHB Tape Specialty Tapes, 2015.

[2] A. Abbad, Développement d'un traitement acoustique basses-fréquences à base de résonateurs d'Helmholtz intégrés à membrane électroactive. Thèse, Université Bourgogne Franche-Comté, Université de Sherbrooke (Canada), 2018.

[3] G.A. Holzapfel, Nonlinear Solid Mechanics – A Continuum Approach for Engineering, John Wiley & Sons, Chichester, New York, 2000.