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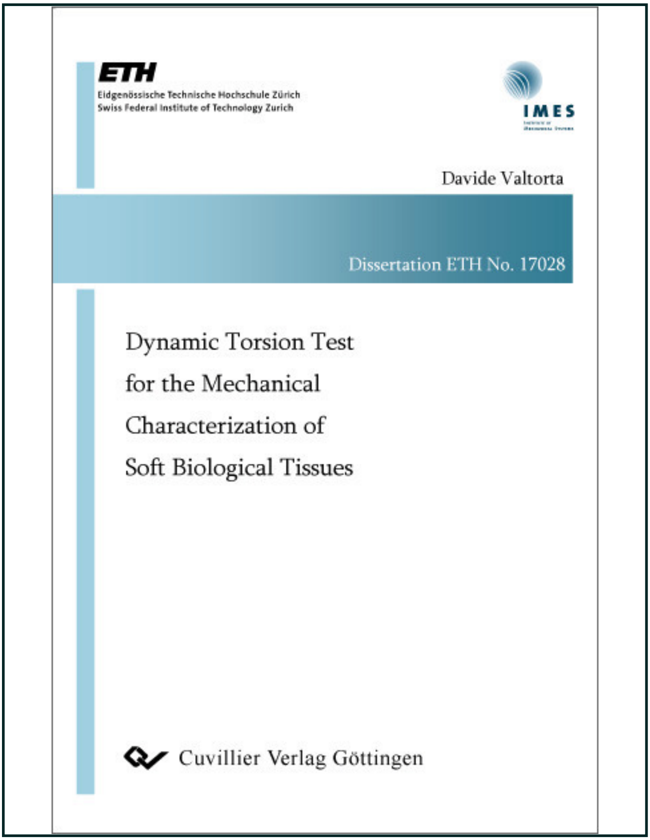
Dynamic Torsion Test for the Mechanical Characterization of Soft Biological Tissues



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Chapter 1

Introduction

Accurate characterization of the mechanical behavior of biological tissues is essential to a number of new computer-aided medical technologies, such as surgical training, planning and development of real-time surgical simulators [6, 14, 69, 86]. Furthermore, mechanical modeling of soft tissues is needed in the development of new surgical tools and can contribute to diagnostics, distinguishing healthy and unhealthy tissues depending on their mechanical response.

In our society, the increasing demand of high-fidelity surgical tools for training, planning, and intra-operative support, has lead researchers to focus their attention on biomechanics, in various aspects of modeling the mechanical behavior of biological tissues. The Swiss National Science Foundation has started in 2001 to fund a major research project, called CO-ME (COmputer aided and image guided MEdical interventions), that involved a network of scientists and engineers with the common task to develop and evaluate basic and applied technologies, required for diagnosis, surgical planning and therapeutic intervention. This work is a part of the CO-ME Project 6, which received the assignment to develop constitutive models to describe the mechanical behavior of soft biological tissues and to create new experimental techniques for the assessment of their mechanical properties.

A new measurement technique for biological tissues has been developed aiming at: (i) obtaining a non-destructive test, suitable for in vivo application during open surgery, and (ii) complementing the existing quasi-static tissue characterization already existing at the Institute of Mechanical Systems, ETH Zurich, namely the Aspiration Device [60, 91].

Experimental techniques for testing biological tissues

Characterizing the mechanical behavior that soft nonload-bearing tissues exhibit is a difficult task. Standard methods for testing soft tissues are needed to produce repeatable results that can be mathematically interpreted in order to describe the natural behavior of the tissue. Mechanical testing of biosolids can be accomplished with different methodologies, mainly grouped into destructive and non-destructive techniques [20, 22, 90].

Destructive testing utilizes material samples directly extracted from organs and experiments are carried out according to standard methods of material characterization, such as tensile, compression and shear tests. In the works of Yamada [94] and Fung [22], a large number of experiments on all kinds of human and animal tissues are described. Among all the methods reported in their works, uniaxial and biaxial tensile tests appear often and are carried out with standard equipment for material tests. One major issue that has to be faced in testing biological tissues with standard machines is however represented by samples preparation and handling [55]. Realizing a precise excision from the tissues analyzed of samples of well defined geometry is a common problem of all these methods. Compression tests are used as alternative to test those samples, whose characteristics do not allow clamping in tensile tests, for example with soft organs such as liver, kidneys, brain or uterus (see e.g. [11, 19, 56, 92]). However, the release of fluids that occurs due to compression of the samples can highly influence the outcomes of these tests. Shear tests have also been carried out using standard rheometers on excised tissues samples (see e.g. [16, 47, 59]). The use of conventional shear rheometers, normally employed in dynamic mechanical analysis of fluids and polymers, enables the viscoelastic characteristics of biological tissues to be investigated up to frequency limits of 10 to 100 Hz.

Non-destructive techniques, in contrast to the methods presented above, present the great advantage of a possible direct application in vivo, during open surgery, avoiding the problems of samples preparation and handling and eliminating the uncertainties due to the alterations of the material when extracted from its biochemical environment [39]. Most of these techniques are based on indentation tests, in which a mechanical indentor probe is pushed against the surface of a tissue sample and the response of the tissue is recorded in terms of force and displacement in time, as in the works of Ottensmeyer [65] and Zheng [100, 101]. An alternative to indentation tests is offered by the so called pipette aspiration technique [3], which sets well defined boundary conditions through the contact of an aspiration tube with a soft tissue sample and yields two dimensional load-deformation data. The aspiration technique was applied during in vivo measurements on soft human organs by Kauer et al. [37] and recently by Nava et al. [61].

Major research efforts have also been made to use non-invasive imaging methods such as ultrasound and magnetic resonance for the evaluation of soft tissue elasticity parameters [23, 27]. These methods, which combine mechanical deformation and measurement of resulting strain fields to extract elasticity data, allow a characterization of tissue regions that are not directly accessible with standard testing methods. Among these imaging techniques, elastography [64, 78] and sonoelasticity [41, 45] can be employed in the detection of regional stiffening within one organ. In magnetic resonance elastography (MRE) [58], quantitative measurement of the elastic properties is realized by monitoring the wave propagation field induced in a tissue by an external mechanical vibrator (see e.g. [42, 51, 82]).

The dynamic torsion test

This work aimed at developing a new non-destructive testing method for soft tissues based on the know-how gained in the last twenty years at the Institute of Mechanical Systems, ETH Zurich, on torsional vibrating sensors. Dynamic testing, instead of quasi-static, is performed by making a material sample part of a vibrating system and achieves a material characterization in the frequency domain, giving useful information about the strain rate dependence of the mechanical properties of the samples analyzed.

Sensors based on forced torsional oscillations and dynamic shear tests are widely employed in research and industrial processes in several application fields. A good review of this measurement technique and of the design of torsional resonating probes is reported by Langdon [43]. The Institute of Mechanical Systems, ETH Zurich, has developed several sensors based on this working principle and applied them in the rheological characterization of fluids and suspensions at high frequencies with the works of Dual, Goodbread and Sayir [18, 79] and more recently by Häusler, Hochuli and Romoscanu [29, 31, 75]. In their works, they presented torsional resonating probes vibrating at high frequencies (always above 1 kHz) to measure the viscoelastic properties in shear of viscous fluids [18], polymers and suspensions [75], bitumen [31], blood [29]. High frequency rheometry is useful to characterize the viscoelastic properties of polymers and fluids and can give information about their microstructure [21] by observing their typical frequency dependent behavior. The study of the material response at different frequencies, and thus different wavelengths, allow investigating the influence of the tissue microstructure on the mechanical behavior of soft biological tissues.

In this framework, a new non-destructive technique to measure the mechanical properties of soft tissues was developed: the *dynamic torsion test*. The mechanical response of viscoelastic materials is characterized for harmonic shear deformations performed at high frequencies (1-12 kHz) and small strains (up to 0.2% nominal strain for the soft biological tissues considered). Experiments are performed using a torsional resonating sensor, hereafter referred to as the torsional resonator device (TRD), which consists of a rod excited to vibrate at resonance, with one end in contact with a material sample. The TRD induces shear waves in the material analyzed through forced torsional oscillations: the viscoelastic properties of the material are derived from the results of the interaction between the sensor and the material sample considered. This technique complements the Aspiration Device [60] and allows obtaining a characterization of soft tissues in a wide range of strains and loading rates.

Outline of the present work

In this thesis, a novel experimental method for the mechanical characterization of soft biological tissues was developed. Several aspects has to be faced in the development of a new measurement technique:

(i) the sensors design, with features that must be tuned to the application considered here: in particular, the experiment must provide well defined kinematic and static boundary conditions,

(ii) the mechanical modeling of the interaction between sensors and soft tissues, that is crucial for the quantitative evaluation of the experimental results,

(iii) the analysis of the scatter in experimental results, error sources and uncertainties in the measurements.

The dynamic torsion tests was thought specifically for biomechanics and resulted in the design of a sensor, the torsional resonator device (TRD), that is able to characterize soft biological tissues. Nonetheless, this measurement technique can be applied to different applications fields, exploiting always the same working principle. Collaboration with the EMPA, Swiss Federal Laboratories for Material Testing and Research, has showed how this measurement technique can be effective in the mechanical characterization of synthetic material as silicone rubbers, bituminous binders, and electroactive elastomers.

The measurement principle of the dynamic torsion test is described in Chapter 2. Details on the experimental technique are reported, along with the description of the design of the devices used and the mechanical models that describe their dynamic behavior. The sensors presented in this work are able to measure the torsional mechanical impedance of the material samples analyzed, that will be then link to their viscoelastic properties.

The torsional mechanical impedance measured with a sensor can be related to the rheological properties of the material analyzed by using a model that accurately describe the interaction between torsional vibrating sensor and material sample. In Chapter 3, the elastodynamic problem of forced torsional oscillations that describe the interaction is solved, using analytical and finite element approaches. A discussion about the suitability of the dynamic torsion test for different application fields is also included, highlighting the most important factors that must be controlled during a test and the inherent error sources.

Chapter 4 deals with the characterization of soft biological tissues with the torsional resonator device. The measurement technique is first validated with comparative wave propagation experiments on silicone phantoms that mimic the mechanical properties of soft tissues. Then, results obtained ex vivo on bovine internal organs are presented. The viscoelastic behavior of liver, kidney and uterus is characterized at high frequencies. Discussion on the application of this method in biomechanics is provided, along with an analysis of the error sources and possible improvements of the method.

The dynamic torsion test, developed for the main purpose of characterizing soft biological tissues, is applied in Chapter 5 to synthetic material. Here, the results of a collaboration with the EMPA are showed (i) in studying the aging process of bituminous binders, that influences the efficiency of road pavements, and (ii) for the mechanical characterization of electroactive polymers, showing the effectiveness of this measurement method in different application fields.

Finally, the achievements of the present works are summarized in Chapter 6.

Chapter 2

The Dynamic Torsion Test

This chapter describes the measurement principle of the dynamic torsion test. In this test, forced torsional oscillations are exerted by a vibrating sensor on a material sample in order to characterize its viscoelastic behavior. Details on the measurement principle of this technique are reported, along with the description of the design of the devices used and the mechanical models that describe their dynamic behavior. The execution of a dynamic torsion test provides the measurement of a mechanical quantity, the torsional impedance, that will be linked in Chapter 3 to the material properties of the medium analyzed.

2.1 Introduction

The mechanical properties of viscoelastic materials are determined in this work using a dynamic test. In a dynamic test, the material sample under investigation is made part of a vibrating system (usually a shaker or a resonating sensor) and the material properties are extracted by measuring the change in the dynamic behavior of the system. In this thesis, the sensors analyzed are excited to vibrate at their torsional natural frequencies. This test is based on the principles of the so-called *resonance methods* [10, 28, 68] widely used in parameters identification and structural mechanics: here, the structure under analysis consists of a vibrating sensor, whose geometry and properties are given, and a material sample of unknown properties.

Use of oscillating probes for the characterization of the rheological properties has been proposed for fluid films [18, 43, 54, 80] and suspensions [75]. These sensors consists of tubes or pipes excited to vibrate in torsional resonance and interacting with a viscoelastic material. The know-how in the application of this technique at the Institute of Mechanical Systems, ETH Zurich, dates back to the late 80s with the work of Sayir, Dual and Goodbread, [18, 79]. This technique was applied to the viscometry of fluids, later extended to the rheology of suspensions [75], bituminous binders [31], and recently in biomechanics with a blood viscosimeter developed by Klaus Häusler [29].

This thesis deals with the development of a similar measurement method based on forced torsional oscillations, where sensors are excited to vibrate at their eigenfrequencies. These sensors consists of rod-shaped vibrators, whose lower extremity is laid on the top of a material sample. In contrast to existing devices, the sensors presented in this work interact with the material samples only through the contact area at the lower extremity of the rod-shaped sensors. In some cases, the contact are can also include the sides of the sensors. The mechanical properties are derived from the material response to harmonic shear in the linear viscoelasticity range at high frequencies (1-12 kHz).

The proposed measurement method has been used for different applications, always exploiting the same principle: (i) in biomechanics, for the determination of the viscoelastic properties of soft biological tissues; (ii) for the characterization of synthetic materials, as silicone rubbers and polymers; (iii) in bitumen rheology, to monitor the evolution of the viscoelastic properties due to exposure to environmental influences. The specific conditions and working environments typical of these various application fields require the development of a different design for the devices employed, whose features will be described in this chapter.

In Section 2.2, the working principle of this class of torsional resonating sensors is presented, along with the control electronics used to measure the changes in their dynamic behavior. The design of the vibrating sensors used in this thesis are presented in Section 2.3. These are: (i) the torsional resonator device (TRD) developed for soft biological tissues and (ii) the high frequency torsional rheometer (HFTR), used in viscometry of fluids and for the characterization of synthetic materials. A crucial point in the development of a measurement technique based on dynamic testing is represented by the mechanical modeling of the sensors. Their dynamic behavior must be accurately modeled and the interaction with the viscoelastic medium is characterized in terms of a quantity, the torsional mechanical impedance, that will be used (as described in Chapter 3) to extract the material parameters of the material samples.

2.2 Measurement principle

Figure 2.1 shows a simplified scheme of the dynamic torsion test. The torsional vibrator consists of a cylinder made of metal (i.e. steel, aluminum or brass, of known material properties G_s^* and ρ_s) driven in torsional oscillations by an electromagnetic transducer. The transducer applies a torque $M_e(t) = \hat{M}_e e^{j2\pi ft}$, a time harmonic function with frequency f, with $\hat{M}_e$ indicating the amplitude of the torque in complex notation. The rotation of the sensor around its axis is described by the angle $\theta(x,t) = \hat{\theta}(x)e^{j2\pi ft}$ that is also a harmonic function.

The lower extremity of the sensor is in contact with a material sample that is assumed to behave as a homogenous, linear viscoelastic material of unknown properties G^* and ρ. This assumption, that considerably simplifies the problem, will be discussed in detail in the next chapters, depending on the materials and testing conditions considered.

The frequency of excitation f is chosen to be close to one of the torsional eigenfrequencies of the mechanical system (vibrator+viscoelastic medium). The sensor is indeed a resonator, i.e. a device that vibrates around its eigenfrequencies. The techniques available for parameters identification of a mechanical system at resonance (*resonance methods* [10, 28, 68]) can be employed.

An important issue in resonance testing is represented by the choice of geometry, design and material of the torsional resonator that determine the eigenfrequencies of the system. The sensors considered in this thesis have resonance frequencies in the range 1-12 kHz: therefore, the viscoelastic material samples will be tested in this frequency domain. The use of a resonance method implies a technique that is not spectroscopic, i.e. a full frequency characterization of the materials is not allowed: they will be characterized only in correspondence to the eigenfrequencies of the sensor chosen (discrete characterization in the frequency domain).

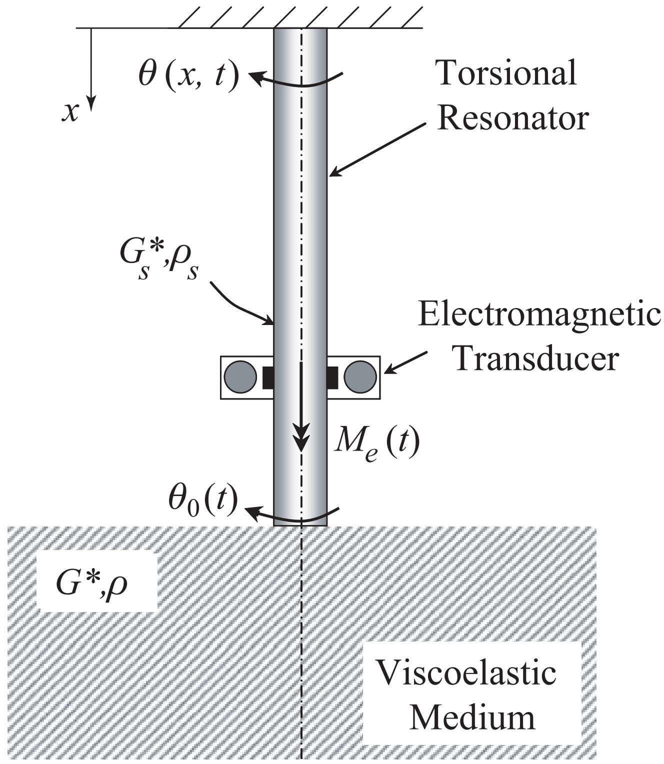

Figure 2.1: *The dynamic torsion test: scheme of the torsional resonator interacting with a viscoelastic medium.*