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Resonant vibrating sensors for tactile tissue differentiation

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Abstract

Surgical resection of brain tumours is a difficult task. To enhance surgery results, a tactile sensor is wanted that gives better resolution and sensitivity than the human tactile sense. The characteristics of resonant vibrating piezoelectric elements change with varying load. This allows for calculation of mechanical load parameters by measuring electrical quantities. Different setups of piezoelectric sensors have been used to investigate soft materials. Finally, a piezoelectric bimorph sensor gave good results for distinguishing tissue mimicking gel-phantoms with different gelatine concentrations.

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1. Introduction

At surgical resection of tumours the surgeon has to fulfil a very difficult task: on the one hand the tumour should be fully excised so that the patients' healing is achieved or—in case of malignant tumours—the time to tumour relapse is maximised. On the other hand the surrounding tissue should be treated with maximum care. Especially, in neurosurgery resection borders should strictly meet the tumours dimensions. Otherwise the patient may become disabled by speech disorder (lalopathy), impaired vision, hemiplegia or alertness dysfunction.

Today, surgeons rely on their experience and additional apparative techniques: after localising the tumour by the use of imaging techniques like computer tomography (CT), magnetic resonance tomography (MRT) or ultrasound, the resection can be done using a intra-operative microscope. Neuronavigation enhances the localisation before skull opening, but afterwards most often severe brain-shift appears due to pressure change. Intra-operative CT or MRT, which is costly and time consuming, is needed to relocate the tumour and to get reliable navigation results.

At last, the surgeon has to decide where and what to resect based on his own senses. Often, visual information is quite poor due to minimal differences in colour and structure of intact brain parenchyma and tumour tissue. Digital image processing or spectral analysis could possibly deliver valuable information, but

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both are based on optics which easily contaminate or may be irritated by surface fluids. Thus, the key information is given by tactile sensing.

Since human sense of touch is a highly complex sensory perception mechanism, it is challenging to provide a tool for intra-operative tactile sensation that provides at least same resolution and sensitivity. Having a sensor, that evaluates mechanical characteristics of the tissue—in particular stiffness and damping—much more accurate than the surgeon himself, would additionally enhance surgery prosperity. But mechanical design as well as evaluation effort is restricted to strong limits: the system must not disturb the surgeon and has to allow real time operation so that the surgeon gets the needed information immediately.

2. Resonant vibrating sensors

Standard techniques to determine the stiffness of materials are based on force and elongation/depression measurements that could be done for example by strain gauges. Derivation of damping is most often done by evaluating pulse or step response. To integrate multiple sensor elements in restricted volume and/or applying different measurement sequences in short time can be avoided if one technique element gives all needed information.

Known from other technical applications like ultrasonic welding and machining or ultrasonic acoustic devices, the electromechanical characteristics of resonant vibrating structures vary strongly with their load. Especially, for devices having nonlinear contact, eigenfrequency and amplitude of the vibration change depending on the kind of load. Typically, this behaviour is unwanted for the process and thus control algorithms are used to cancel them out. But vice-versa, the load may be characterised by interpreting the change in characteristics of a resonant vibrating sensor. This principle has already found multiple application, e.g. pressure and chemical sensors or monitoring of bond quality [1,2].

Applying this technology for medical use has already been proposed by AXIOM [3]. They built up several resonant vibrators to investigate stiffness of inner organs, skin stiffness, and intraocular pressure. Pressure force, depression, and frequency shift of the vibrator were evaluated to determine the stiffness parameters. Unfortunately, there are no news about these devices since 2003. May be, that other sensor techniques overrode the resonance principle in those special fields of application?

Fig. 1 depicts a simple lumped parameter model that describes a resonant vibrating piezoelectric element acting against a load. The mechanical behaviour of the free vibrator is characterised by its modal mass, damping and stiffness. The electrical behaviour is included in the model using electro-mechanical analogies. The electrical capacitance and resistance of the piezoelectric element are represented as a mechanical compliance and a mechanical damper, respectively. The electro-mechanical coupling is represented by a rigid lever that converts electrical to mechanical quantities. Thus, its transformation is not given by a dimensionless

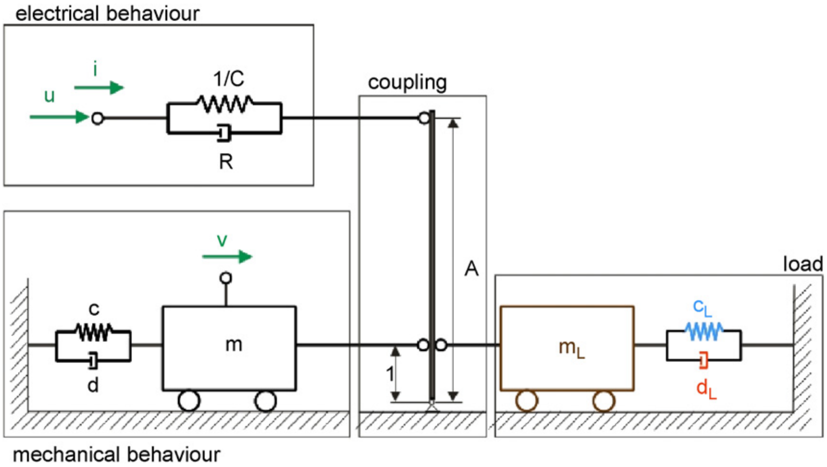

Fig. 1. Mechanical model for resonant vibrating piezoelectric element with load.

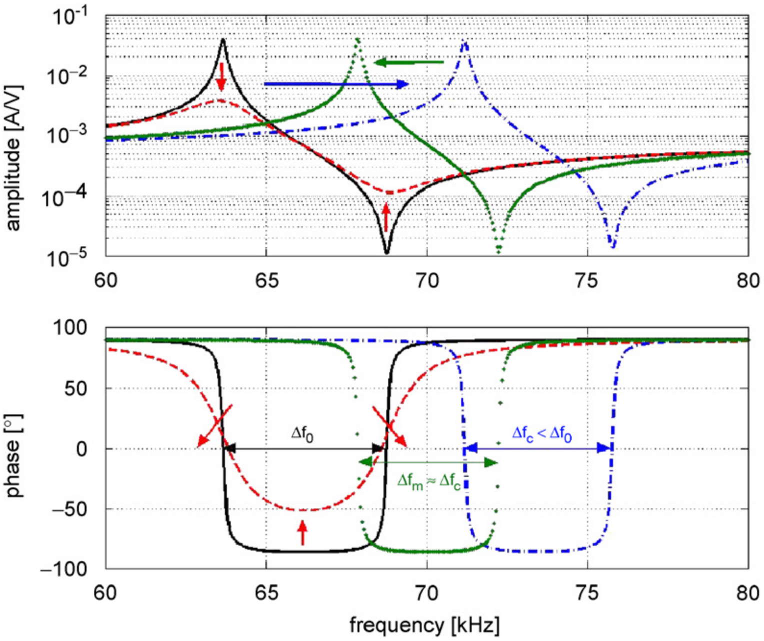

Fig. 2. Simulation of electrical admittance characteristics for different sets of load parameters: — $c_L = 0, d_L = 0, m_L = 0$; - - $c_L = 0, d_L > 0, m_L = 0$; - · - $c_L > 0, d_L = 0, m_L = 0$; and · · · $c_L > 0, d_L = 0, m_L > 0$.

factor, but carries the unit [N/V] = [As/m]. The load characteristics are depicted by an additional mass that has to be moved, some damping and counteracting stiffness. For hard contact mechanics some contact models should be included, but for soft contact it is assumed that the vibrator stays in contact all the time and nonlinear effects like stick/slip or contact/noncontact do not appear.

Simulation results for different load characteristics are depicted in Fig. 2. Pure load stiffness leads to an increase of resonance frequency and anti-resonance frequency of the vibrator. As both do not increase by the same value, k_{eff}^2 decreases. The same effect can be found using simplified equations that apply for small damping values:

$$f_r \approx \frac{1}{2\pi}\sqrt{\frac{c + c_L}{m + m_L}}, \tag{1}$$

$$f_a \approx \frac{1}{2\pi}\sqrt{\frac{c + c_L + \frac{A^2}{C}}{m + m_L}}, \tag{2}$$

$$k_{\mathrm{eff}}^2 \approx \frac{f_a^2 - f_a^2}{f_r^2} \approx \frac{\frac{A^2}{C}}{c + c_L + \frac{A^2}{C}}, \tag{3}$$

$$\hat{x}|_{f_r} \propto \frac{1}{d + d_L}. \tag{4}$$

Counteracting to a load stiffness, load mass reduces resonance frequency and anti-resonance frequency, but it does not affect k_{eff}^2. Load damping—as long as it is not too large—changes frequency only slightly but has strong impact on amplitude and phase at resonance and anti-resonance. Large damping may even lead to loss of zero-phase crossing. This might cause troubles in finding resonances, if automated strategies are used in electrical drive-circuits [4].

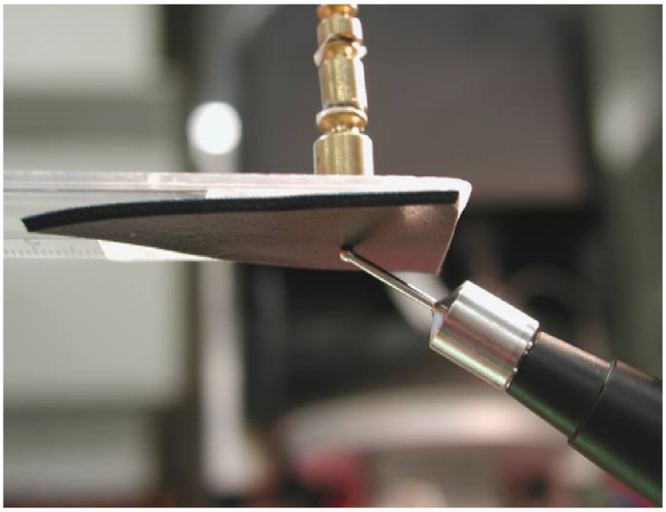

Fig. 3. Ultrasonic scaler with specialised tip geometry used for investigation of gel-phantoms of different gelatine concentration.

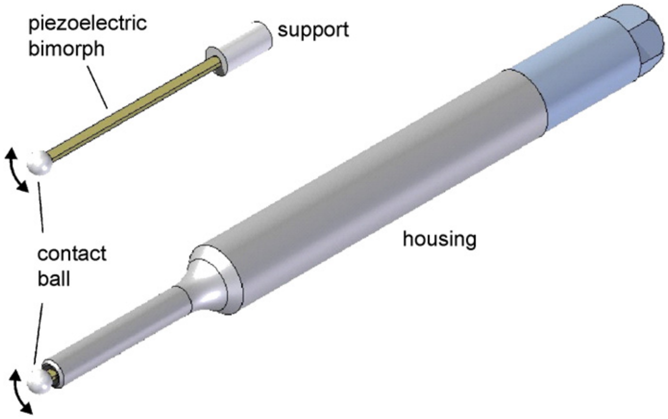

Fig. 4. Piezoelectric bimorph sensor, arrows indicating direction of vibration.

3. Experimental setup

A trial setup was done using an ultrasonic scaler which typically a dentist uses to scale teeth. A special tip was designed to amplify vibration amplitude and to get a larger contact surface, see Fig. 3. The result was an improved sensibility for amplitude measurements, but frequency shift was barely measurable.

Finally, we set up a new sensor system based on a piezoelectric bimorph, using one layer for the resonant excitation of vibration and the other one as the sensing element, see Fig. 4. The main benefit of this design is its sensitivity in amplitude. Tissue mimicking gel-phantoms of different gelatine concentration could easily be distinguished.

The sensor can be driven in two modes. Mode 1 is based on resonance control using a phase-locked-loop. Instead of the driving current, which is typically used, control is done by the generated sensor voltage, because electrical admittance is strongly damped and does not show zero-phase crossing. Of course, control could be done anyway, e.g. using adaptive PLL control [4], but the easier and more reliable way is to use the stable sensor voltage signal. The shift in resonance frequency and sensor voltage amplitude at resonance during contact are used for deducing damping and stiffness of the investigated material. Mode 2 uses a fixed frequency close to unloaded resonance frequency. This minders control effort, just the shift of unloaded

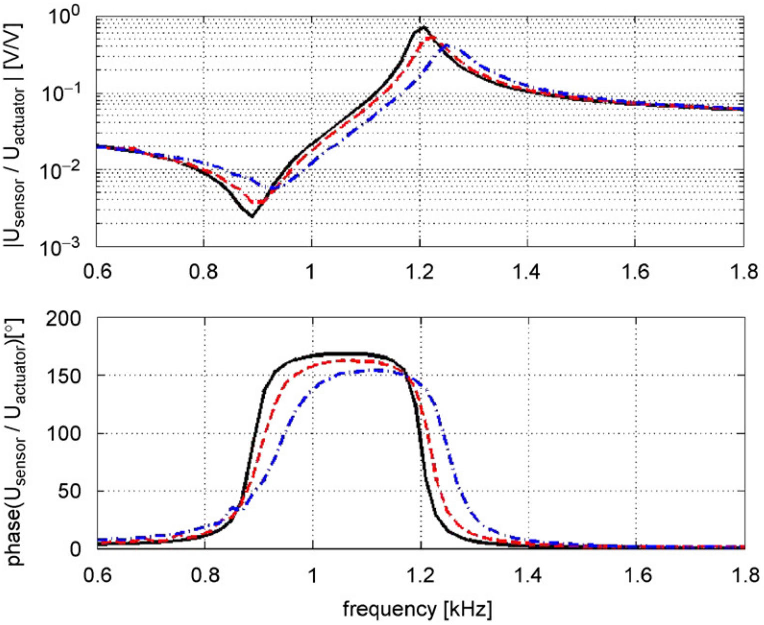

Fig. 5. Dependency of admittance characteristics on pressure force: — without contact; - - minimum contact pressure; and - · · - moderate contact pressure.

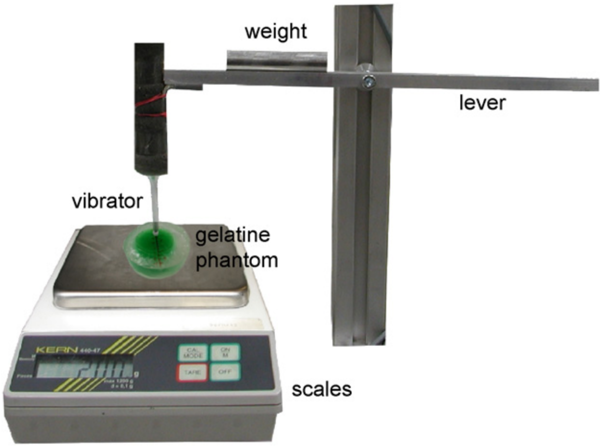

Fig. 6. Measurement setup using vibrating bimorph sensor.

resonance frequency caused by thermal load or else should be balanced. For mode 2 amplitude and phase of the ratio of sensor and actuator voltage are evaluated.

A crucial point for credible evaluation of the bimorph measurements is an additional measurement/control of pressure force. Increasing pressure enlarges the contact area and thus effective stiffness and damping increase, see Fig. 5. During lab-use stability of force value was assured using a weight, see Fig. 6. Additionally, the bimorph sensor showed some sensitivity to contact angle and related vibration direction but at constant values, measurement results look promising, see Fig. 7. The sensor voltage and resonance frequency for mode 1 operation as well as the phase of the voltage-ratio from sensor and actuator clearly indicate different gel-phantoms. Borders between different areas are not sharp due to boundary effects. To get precise information for resection will thus be delicate. Experiments on animal brain tissue will follow to get sure about feasibility of the gel-phantoms.

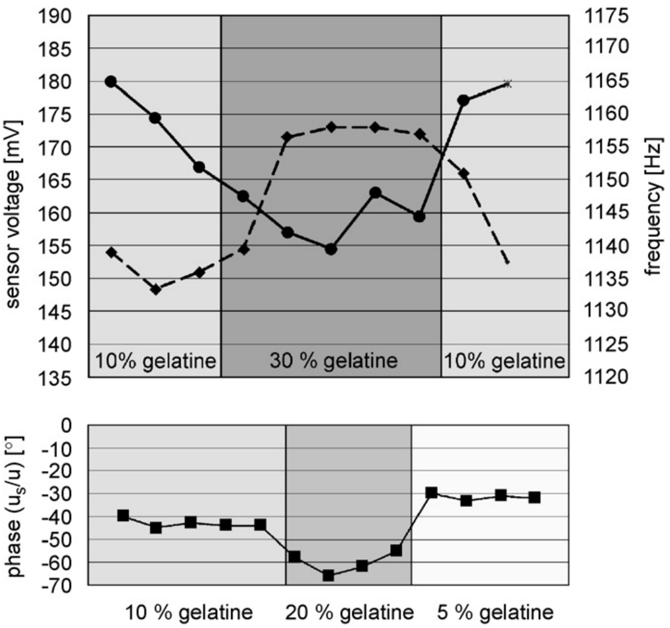

Fig. 7. Measurement results on gel-phantoms with different gelatine concentration: (a) using resonance control: • amplitude of sensor voltage and ◇ driving frequency; and (b) using fixed frequency: phase between sensor and actuator voltage.

4. Conclusions

Using model-based design we developed different resonant actuator–sensor systems to apply on characterisation of soft materials. The detection and evaluation of frequency shift and amplitude variation of the fundamental and higher harmonics allow for the differentiation between distinct media that imitate the mechanical characteristics of tumour and healthy tissue.

Next step is to improve the sensor system in such a way that it is utmost sensitive to load changes but not to manual handling. Spatial resolution should be increased to define precise resection borders. The resulting tool will enhance surgeon's decision base to achieve best possible surgery results.

Acknowledgements

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