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Tactile tissue characterisation by piezoelectric systems

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Abstract For devices having non-linear contact, load plays a fundamental role. Variations in the characteristics of the load cause change in eigenfrequency and amplitude of the vibration. In most technical applications, this unwanted behaviour is cancelled by the use of control algorithms. However, multiple applications, like bond quality monitoring or chemical and pressure sensors, have found that the load may be characterised by interpreting the change in characteristics of a resonant vibrating device used as a sensor. Surgical resection of tumours is a very difficult task. After localising the tumour by the use of imaging techniques, the resection demands the surgeon to decide where and what to resect based on visual and tactile differentiation of tumour and healthy tissue. Exactness of this process could be enhanced if we can provide the surgeon with a device capable of evaluating mechanical characteristics of the tissue much more accurately than the surgeon himself can do. As the mechanical characteristics of tumour and healthy tissue differ but slightly, the task is to design a system with high sensitivity. Therefore, we have developed a resonant actuator-sensor that allows the differentiation among distinct media that have similar mechanical characteristics to tumour and healthy tissue using a piezoelectric bimorph. The design is based on the detection and evaluation of frequency shift and amplitude variation of the fundamental and higher harmonics using one layer for the resonant excitation of vibration and the other one as the sensing element.

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1 Introduction

Brain tumour surgery is based on a micro-neurosurgical concept, which has been introduced with his work by the Turkish neurosurgeon G. Yasargil [1]. Since then the neurosurgeon uses among others a floating binocular microscope and a specialised set of microsurgical instruments for the resection of tumourous brain tissue. Using a microscopically enlarged aspect of the intraoperative situs and based on his experience, he will differentiate brain tumour tissue from healthy, or at least edematous altered, but functionally intact or recoverable brain parenchyma. It is of substantial importance for the postoperative patient outcome to perform this differentiation with highest precision especially in eloquent, i.e. neurological crucial areas to assure on the one hand protection of functionally relevant healthy brain tissue and on the other hand to resect the tumour completely. Even for high-grade gliomas, the extent of tumour resection corresponds to survival time [2].

In addition to this visual information, and maybe to a more subconscious extent also the neurosurgeon's sense of touch is of crucial relevance in the tissue differentiation. Tissue elasticity differences are transferred to the neurosurgeon's hands by the instruments used for the tissue ablation and manipulation during surgery. At the border of the tumourous area or in low-grade glioma differences to healthy brain tissue becomes less evident implying a risk of inappropriate tissue resection.

In spite of the outstanding importance of neuronavigational techniques, neuronavigation is based on preoperative imaging scans. Considerable brain shift may occur during

Fig. 1 Tactile transducer based on piezoelectric bimorph

surgery, which will lead to erroneous results [3]. Intraoperative magnetic resonance imaging is a worthwhile [4] but still high priced and even time-consuming technique. While intraoperative ultrasonic imaging [5] can deliver highly reliable results in the detection of tumourous tissue, employing this technique requires wide experience.

For the detection and characterisation of different tissue, Hatakeyama et al. [6] has developed a tactile piezoelectric sensor system. These sensors are not commercially available anymore and presumably not sensitive enough to be used during neurosurgery. The development of a tool for intraoperative tactile perception supporting the intraoperative distinction of tissue consistency with higher sensitivity would be promising to improve safety during surgery.

Sensing techniques used in the field of ultrasonic bonding machines revealed that it is possible to characterise stiffness and damping of the load by the evaluation of amplitude and phase between excitation and response signals of the electromechanical system [7]. Transferring and adapting this technology to medical requirements may improve tumour resection strategies, therefore extend lifetime, and ameliorate outcome for patients.

2 Material and methods

A transducer based on a resonant driven piezoelectric bimorph was developed. The bimorph is composed of two

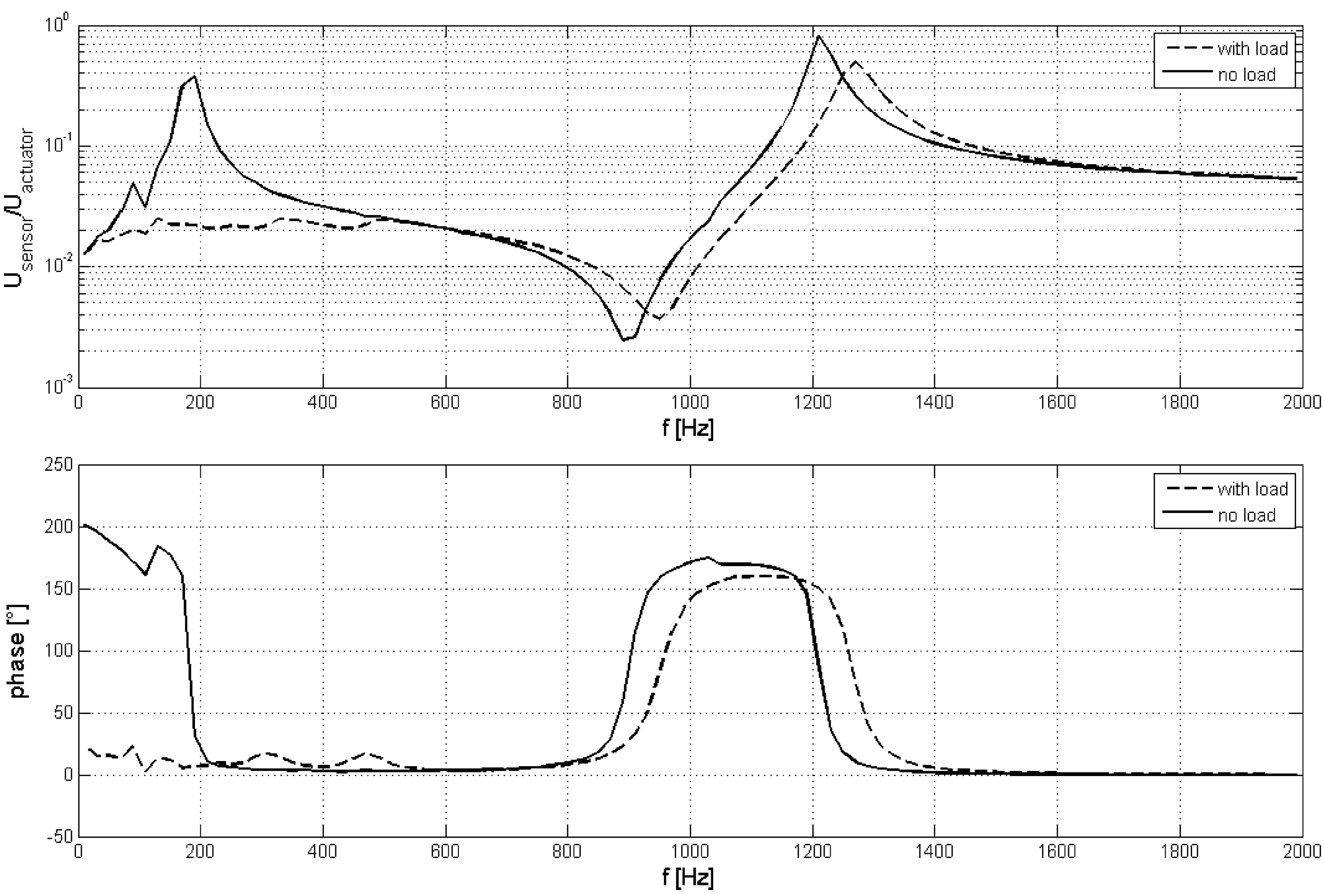

Fig. 2 Signal-dependency ($U_{\mathrm{Sensor}}/\mathrm{U}_{\mathrm{Actuator}}$) during frequency sweep up to 2,000 Hz

piezoelectric elements contacted to a common cantilever. The bimorph has a ball-shaped tip for tissue contact. The bimorph is covered by a jacket tube, see Fig. 1.

While one of the piezoelectric layers is used to drive the bimorph, the other one is used as a sensor element. The ratio of both voltages depends strongly on the dynamics and on the load of the electromechanical system. Figure 2 shows amplitude and phase of the system's voltage transfer function measured at excitation with different frequencies.

The first resonance peak is related to the first resonance of the vibrating bimorph. At this frequency, the bimorph is too sensitive to external loads. Vibration breaks down at even slight loads, thus resonance control or reliable evaluation of the behaviour is impossible. The second peak in the characteristics relates to the third harmonic of the bimorph. A clear amplitude reduction as well as a shift in resonance frequency and a phase change is observed. Thus, this is the right frequency range for operating the device.

Miller et al. report [8], that brain parenchyma shows a viscoelastic effect. As a test system simulating differences in tissue characteristics, series of gelatine phantoms of subtle concentration gradient, varying from 10–20%, was used. The orientation of the bimorph relative to the gelatine gel surface and the pressing force have been kept constant. Preliminary tests showed that these parameters affect the results. Further measurements using an impedance analyser model HP4192A with constant excitation voltage at different frequencies showed that increasing gelatine concentrations result in increasing resonance frequency. The signal amplitude decreases but the phase shift found at maximum amplitudes remains almost unchanged, see Fig. 3.

For further experiments, a measurement system was developed consisting of analogue circuitry for signal processing and a data acquisition system to transfer the data to a computer. A software based phase locked loop (PLL) was introduced allowing rapid determination of the maximum amplitude and its corresponding frequency. Due to an a priori unknown behaviour of the bimorph in the presence of the load, PLL was implemented using fuzzy logic control.

3 Results and discussion

A series of gelatine phantoms measurements with concentrations of gel ranging from 10 to 20 % have been investigated using the PLL-controlled bimorph. The bimorph was pressed to the gelatine surface by a constant force of about 0.1 N. As slight differences in surface contact and material consistency of the gel phantoms might influence the measurement results, experiments have been repeated three times at each of three different spots. Figure 4 depicts the mean value of the measurement results.

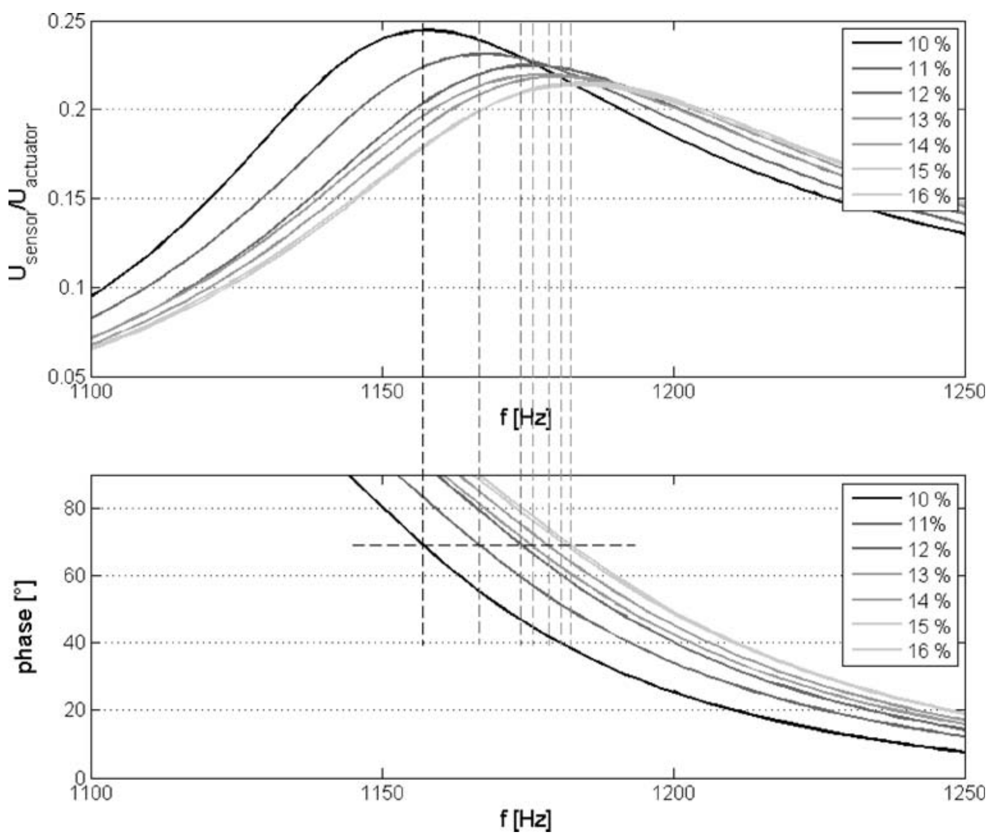

Fig. 3 Preliminary measurements with constant voltage in a frequency range: increasing gelatine concentrations result in increasing resonance frequency, decreasing signal amplitude and constant phase shift at maximum amplitudes

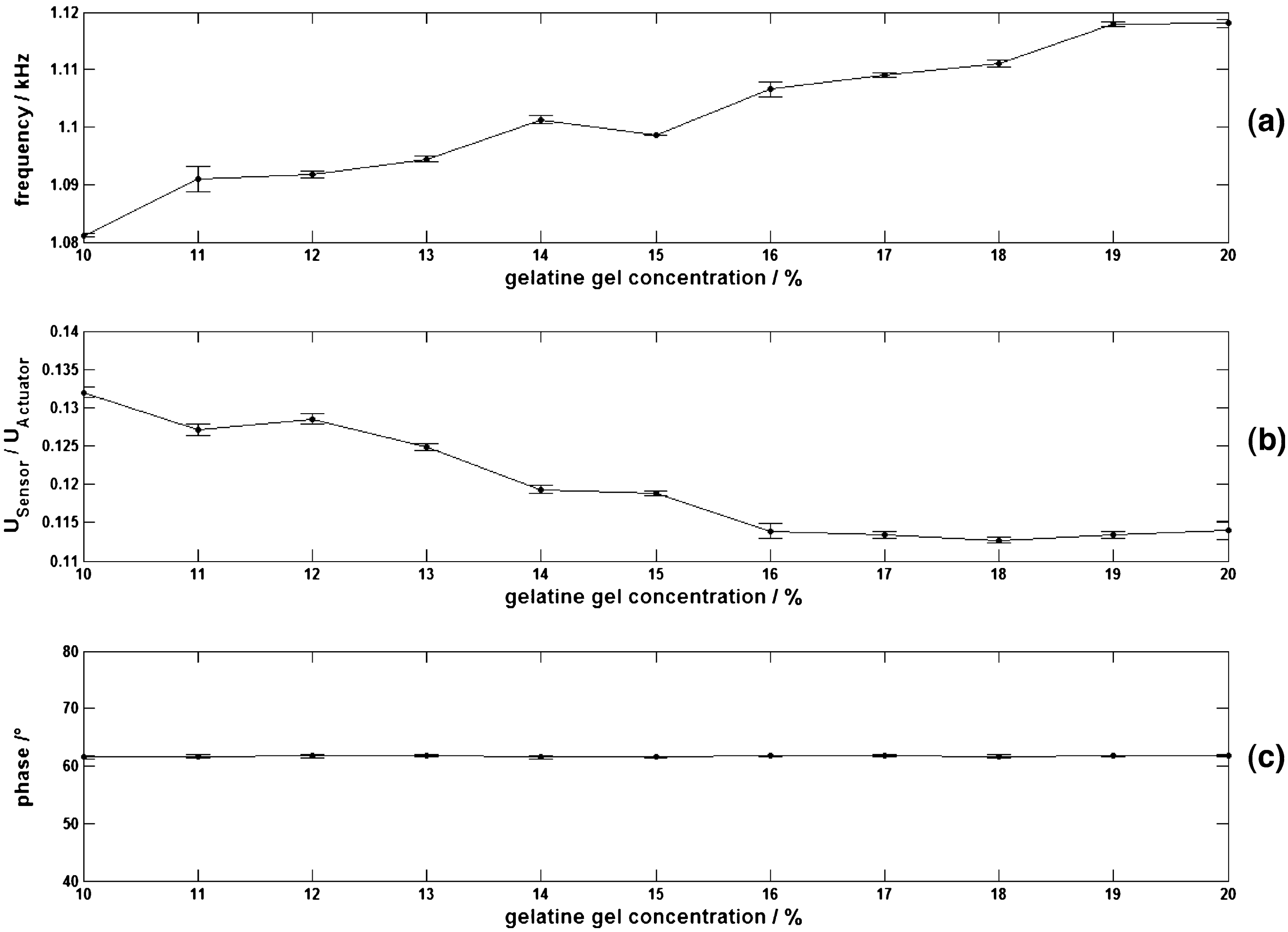

Fig. 4 Measurement results using the PLL-controlled, analogue circuitry: (**a**) frequency of maximum amplitude, (**b**) value of maximum amplitude, (**c**) phase (as a measure of PLL-control quality)for gelatine phantoms with different gel concentrations

Figure 4(a) shows an almost linear dependence of the resonance frequency on the gel concentration. This is quite comprehensible because the stiffness of the gel should increase linearly with the content of gelatine. These results depict clearly the feasibility of using a resonant vibrating bimorph for the differentiation of elasticity differences.

Figure 4(b) shows a similar behaviour for the dependence of the amplitude on the gel concentration, but only for low concentration values. For gel concentrations of 16% and more, the dependency flattens. Possibly, there is a kind of saturation effect due to nonlinearities in the material.

Figure 4(c) illustrates the quality of the PLL in locking to a constant phase.

4 Conclusions

In laboratory conditions, the tactile bimorph sensor system is able to detect even minimal differences in gelatine gel phantoms. Sensor sensitivity actually exceeds human capability of differentiating minimal elasticity distinction.

The necessity of controlling impact force and orientation of the bimorph systems for the tissue contact requires further development for usage of the transducer as a hand guided instrument, which could advantageously be used intraoperatively, and whose results are immediately interpretable. Ideally it would be a sterilisable and therefore a cost-efficient system.

In the increasing field of intraoperative robotics, controlling impact force and orientation of the bimorph systems could be achieved more easily. Adapting a bimorph tactile sensor via a forcetorque sensor to the end effector of a robot for tissue impact control could supply a valuable instrument.

Though tissue elasticity as determined by the tactile sensor system cannot be a stand-alone criterion for the identification of tumourous tissue, it is however intended as an add-on for neurosurgeons or even other subspecialities to increase patient safety during surgery.

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References

1. J.M. Tew, Neurosurgery **45**(5), 1010 (1999)
2. Y. Ushio, M. Kochi, J. Hamada, Y. Kai, H. Nakamura, Neurol. Med.-Chir **45**, 454 (2005)
3. P. Hastreiter, C. Rezk-Salama, G. Soza, M. Bauer, G. Greiner, R. Fahlbusch, O. Ganslandt, C. Nimsky, Med. Image Anal. **8**(4), 447 (2004)
4. C. Nimsky, O. Ganslandt, M. Buchfelder, R. Fahlbusch, Neurol. Res. **28**(5), 482 (2006)
5. G. Unsgaard, T. Selbekk, T. Brostrup Muller, S. Ommedal, S.H. Torp, G. Myhr, J. Bang, T. A. Nagelhus Hernes, Acta. Neurochir. **147**(12), 1259 (2005)
6. Y. Hatakeyama, T. Ono, N. Sato, H. Sakuma, Y. Koyama, N. Inoue, S. Takenoshita, S. Omata, Fukushima J. Med. Sci. **48**, 93 (2002)
7. M. Brökelmann, J. Wallaschek. Proceedings of IMECE2005 (2005)
8. K. Miller, K. Chinzei, G. Orssengo, P. Bednarz, J. Biomech. **33** (11), 1369 (2000)