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Research Paper

Dynamic modeling of breast tissue with application of model reference adaptive system identification technique based on clinical robot-assisted palpation

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ABSTRACT

Accurate identification of breast tissue's dynamic behavior in physical examination is critical to successful diagnosis and treatment. In this study a model reference adaptive system identification (*MRAS*) algorithm is utilized to estimate the dynamic behavior of breast tissue from mechanical stress–strain datasets. A robot-assisted device (*Robo-Tac-BMI*) is going to mimic physical palpation on a 45 year old woman having a benign mass in the left breast. Stress–strain datasets will be collected over 14 regions of both breasts in a specific period of time. Then, a 2nd order linear model is adapted to the experimental datasets. It was confirmed that a unique dynamic model with maximum error about 0.89% is descriptive of the breast tissue behavior meanwhile mass detection may be achieved by 56.1% difference from the normal tissue.

1. Introduction

Soft tissue response to a special pattern of loading is a challenging area in medical diagnostic procedures and surgical operations. Loading may be applied by physical examination (palpation) which is the primary tool in abnormalities' detection. Increasing accuracy of palpation is desirable for better detection and can be achieved by applying a quantitative pattern of palpation. Many experimental and numerical researches provided the fact that soft tissue has a time-dependent viscoelastic behavior (Heverly et al., 2005) which makes it very sensitive to the pattern of loading. Estimation of time-dependent behavior provides tissue's dynamic model. This model can be used for making a medical diagnosis and facilitates physician's task in characterizing tissue behavior. However, still for identification of tissues' dynamic model, it is necessary to apply a quantitative palpation. Artificial tactile sensing (*ATS*) is a new non-invasive method for applying quantitative palpation on the tissue surface. *ATS* outputs would be implemented for tissue characterization which has been the target of many experimental work and numerical modeling. Kim et al. (2014) applied an elastic Finite Element Model (*FEM*) for prostate to achieve the quantitative properties of prostate tissue and the containing tumor. Astrand et al. (2014) utilized tissue phantoms for mimicking cancerous tumors embedded in soft tissue. A tactile resonance sensor

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was used to detect the tumors. Wahba et al. (2014) used an elastic *FEM* for breast cancer diagnosis in a breast phantom with application of *ATS*. Robot-assisted devices equipped with *ATS* are accurate enough to evolve traditional physical examinations. A number of robotic devices have been introduced to apply specified strain in many clinical fields (Ottensmeyer, 2001; Ottensmeyer et al., 2004; Dargahi et al., 2005; Ahn et al., 2012; Mojra et al. 2011, 2012a,b). Ottensmeyer (2001) and Ottensmeyer et al. (2004) developed a minimally invasive instrument (*TeMPeST 1-D*) that measures the mechanical properties of intra-abdominal organs. Dargahi et al. (2005) developed a tooth-like endoscopic grasper which has been equipped in a particular arrangement with a tactile sensor to measure tissue tactile properties such as force and softness. Ahn et al. (2012) utilized a robotic palpation system to estimate the mechanical properties (elasticity) of normal and cancerous prostate tissues. Mojra et al. (2011, 2012a,b) provided a robotic device equipped with a pressure sensor (*Robo-Tac-BMI*) to detect breast tumors and extract tumor characteristics from mechanical parameters. Dynamic system identification is accomplished by estimation of the related models' parameters. Numerical methods have been widely used in this area. Typical numerical identification methods include the Newton methods, the least squares and the gradient search (Li et al., 2012; Li, 2013; Dehghan and Hajarian, 2012). Parameter estimation is also used in the filtering; state estimation (Shi and Chen, 2003; Shi and Fang, 2010) and controller design (Ding et al., 2011, 2012; Wang and Ding, 2011). A recursive least squares estimation was proposed for output error moving average systems using data filtering (Wang, 2011). In the area of parameter estimation (Ding et al., 2011; Ding, 2013a–c), Liu et al. (2009) proposed a gradient approach for multiple-input and single-output systems using identification theory and the auxiliary model identification idea and analyzed the convergence of the gradient algorithm for multivariable Autoregressive with exogenous inputs (*ARX*)-like systems (Liu et al., 2010). Xiao et al. (2009) presented a residual based interactive least squares algorithm for controlled autoregressive moving average (*ARMA*) systems. Zhang et al. proposed a bias compensation based recursive least squares method for stochastic systems with colored noises (Zhang and Cui, 2011) and for a class of multiple-input single-output systems (Zhang, 2011). Many dynamic systems have constant or slowly varying uncertain parameters (Liu, 2004). Adaptive control is an approach to the control of such systems. The basic idea in adaptive control is to estimate the uncertain system parameters on-line based on the measured system signals, and use them in the computation of the control signal. Among the various approaches, the technique of model reference adaptive systems (*MRAS*) is an important one. It can be used for direct adaptation of the controller gains, without explicit identification, as well as for identification of the parameters of unknown process (Van Amerongen, 1980). The *MRAS* is used in wide range of scientific field. Liu and Zhang (2010) developed two *MRAS* estimators for identifying the parameters of permanent magnet synchronous motors (*PMSM*) based on the Lyapunov stability theorem and the Popov stability criterion, respectively. The performance of the estimators was compared and verified through simulations and experiments, which showed that the two estimators were simple, have good robustness against parameter variation, and were accurate in parameter tracking. Nagamani et al. (2014) provided an *MRAS* based sensor-less speed estimator which used the error in instantaneous reactive power for speed estimation. They demonstrated that the *MRAS* based method is computationally simple and its closed loop nature reduces steady state errors. They found that the MRAS based scheme is quite robust under all conditions, with almost no steady state error and transient error is less than 3%. Gatto et al. (2013) presented an online discrete-time parameter identification algorithm suitable for surface-mounted permanent magnet synchronous machines (*SPMs*). It was developed by means of the MRAS technique and the Popov Hyperstability Criterion in order to identify *SPM* discrete-time model parameters. Cuong and Minh (2014) proposed a new procedure for designing a direct analog adaptive controller which was based on *MRAS* using Operational Amplifiers (*Op-Amps*). The adaptive controller was designed by using Lyapunov stability theory. They deduced that it is quite simple, robust and converges quickly. Cirrincione et al. (2013) proposed a neural network *MRAS* speed observer suited for linear induction motor drivers and tested experimentally on suitably developed test set-up. Its performance was compared to the classic *MRAS* and the sliding-mode. *MRAS* speed observers were developed for the rotating machines.

In this study breast tissue dynamic behavior was achieved by mimicking the physicians' palpation in an accurate way. A 45 year old woman with a benign mass in her left breast was clinically tested by a robot-assisted device (*Robo-Tac-BMI*) fabricated based on artificial tactile sensing (*ATS*) technology. Stress–strain datasets were collected and a 2nd order linear model was adapted to the experimental datasets by using the *MRAS* technique.

2. Materials and method

2.1. *Design and construction of robotic tactile breast mass identifier (Robo-Tac-BMI)*

A robot assisted palpation device named "Robotic Tactile Breast Mass Identifier (*Robo-Tac-BMI*)" was fabricated as shown in Fig. 1.

Robo-Tac-BMI mainly consists of a miniature pressure sensor, a probe holding the sensor and manipulated by a robotic system based on a Selective Compliant Articulated Robot Arm (*SCARA*) mechanism and two visualization interfaces one for manipulating the device and the other one for receiving outputs of the device. The device is made of three aluminum elements of motion; one to provide a vertical linear motion for initial adjustment of the whole system and two other ones which are jointed together and allow the arms to extend into confined area and then fold up out of the way. A DC motor (12 V, *Buhler 61.077, Germany*) is responsible for the vertical movement of the shaft. Two incremental rotary encoders (*Autonics E50S8, South Korea*) convert rotary position of the arms to an electronic signal. By mathematical calculations these encoders are able to sense the position and orientation of the end effector with respect to a predefined known reference. An incremental linear encoder (*HP, USA*)