Application of ultra-high speed imaging to understand surgical ultrasonic cutting

A. Marek[1a] and F. Pierron[1]

[1]Faculty of Engineering and Physical Sciences, University of Southampton, UK

[a]A.Marek@soton.ac.uk

Abstract. In this contribution we present use of ultra-high speed imaging to understand the mechanics behind efficient use of high-power ultrasonic cutting devices. Using recording rates of up to one million frames per second we show how the force between the cutting tool and the substrate can be time resolved from a series of images. By combining full-field measurements (digital image correlation) and inverse techniques (virtual fields method) we derive a formula for the force based on the measured strains and accelerations across the cutting blade surface. The method is then verified numerically on synthetically generated data as well as applied to a real cutting device.

Introduction

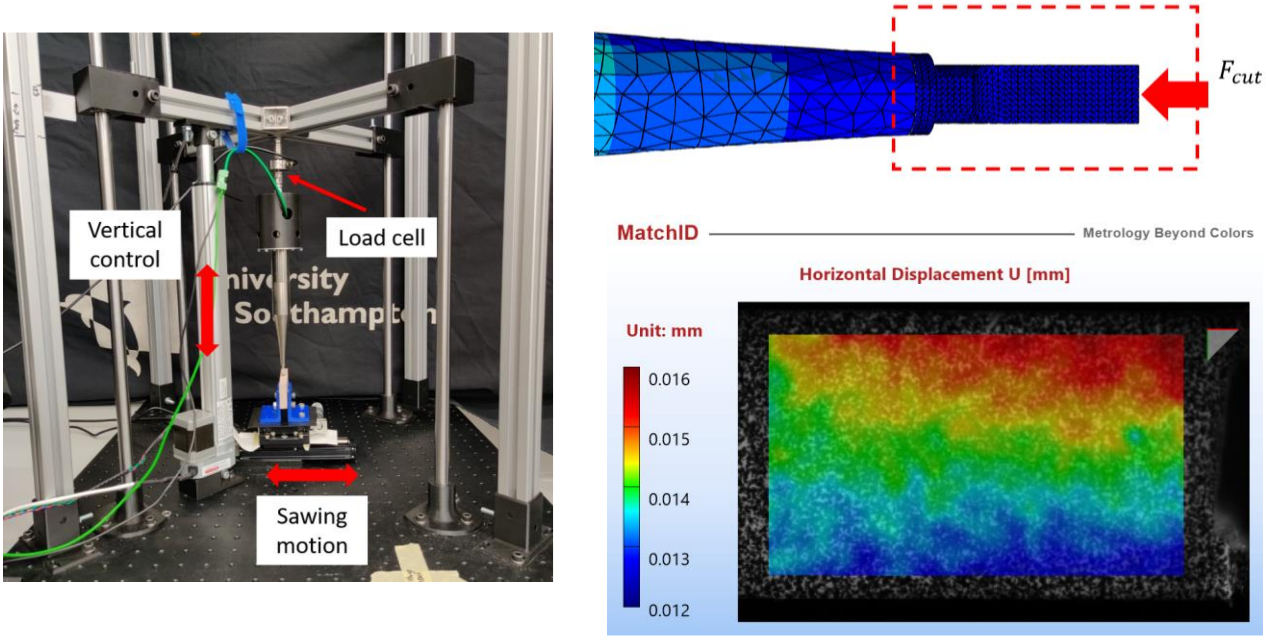
High-power ultrasonic cutting tools have potential to improve many surgical procedures. Compared to standard power tools they offer better precision, reduce blood loss through haemostasis and potentially can facilitate healing through ultrasonically mediated regeneration. Currently there are many commercial tools on the market, such as BoneScalpel™ (Misonix), Harmonic™ shears (Ethicon) or Ultrasonic scalpel™ (Stryker). Typically, the devices work in 20-50 kHz range and provide vibration amplitudes of the cutting blade of about 100 µm in combination of chiselling, sawing, and twisting actions of the blade. The exact mechanics of ultrasonic cutting is not well understood in the context of surgical procedures. Typically, the most important parameter for the tool's performance is vibration amplitude but cutting-related parameters such as feed rate, cutting speed or tool geometry are often underexplored. The most common ultrasonic bone-cutting system studied is orthogonal cutting, which is a simple and effective system to study machining of materials, however it does not represent well the practical application of cutting scenarios. In this contribution we use a chiselling device and control its feed rate using a bespoke automated platform.

Methods

An in-house built ultrasonic cutting tool was utilised in this study designed for a resonance frequency of 25 kHz. The tool had a flat-faced chiselling tip, which was covered with white acrylic paint and covered with a pattern using a microfabricated stamp. The tool was hanged on a motorised gantry which position could be controlled with an actuator (Fig. 1(a)). The vibration of the tool (amplitudes up to 40 µm peak-to-peak) was imaged with a Shimadzu HPV-X, ultra-high speed camera, at 1 Mfps (Fig. 1(b)). Displacement fields over the flat surface of the blade were obtained using digital image correlation and were then differentiated numerically twice in time to obtain accelerations and once in space to obtain strains. These data were then used to calculate the cutting force experienced by the blade using the virtual fields method. The measurement was then repeated for the other face of the blade and the harmonic signal was averaged to remove the effect of strains varying through thickness.

Results

The results of force reconstruction from numerical data are presented in Fig. 2. obtained using simulated images. In that test, the blade was vibrating at 20 µm peak-to-peak with additional 10N of peak force imposed from the impact. As shown in the figure, the proposed methodology correctly reconstructs the force using only strains and accelerations from the blade surface, even when realistic noise level was imposed on the simulated images.



(a) (b)

Fig. 1 (a) Photo of the experimental setup used to image the ultrasonic cutting tool. (b) typical displacement field in the direction of vibration measured over the flat part of the cutting tip.

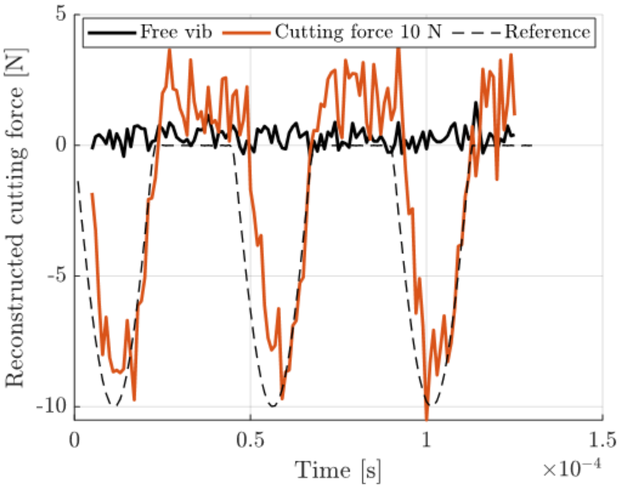


Fig. 2 Reconstructed cutting force from the numerical experiment. Black solid line is a free fibrating tool (nominal force is zero), dashed black line corresponds to repeated impact on the cutting edge.

Discussion

These preliminary results are a stepping stone to develop an experimental platform for studying ultrasonic cutting in the context of surgical application. The ability to time-resolve force is a promising development enabling investigation of its variation with process parameters such as frequency, amplitude or feed rate. The force would not be available otherwise as measuring force at ultrasonic frequencies is not reliable – in this context non-contact measurements open a whole avenue of opportunities.

In future we hope to correlate how the force, temperature raise and magnitude of strains in the work piece depend on tool characteristic as well as processing parameters.