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Incorporating Planar Folded Front Masses in Bolted Langevin-Style Transducers for Minimally Invasive Surgery

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***Abstract*—The Harmonic ACE® (J&J Medical Devices, OH, USA) based on the conventional Bolted-Langevin Transducer (BLT) configuration of piezoelectric transducers is used in robotic surgery due to its fast cutting of soft tissues and improved cut quality. However, the manoeuvrability of the Harmonic Ace® which is the only ultrasonic scalpel compatible with the Da Vinci Surgical System® (Intuitive Surgical Inc., CA, USA) is very limited for the surgeon, due to its long shaft and tool-robot configuration. Till now, there is no existing ultrasonic scalpel compatible with the Da Vinci® Surgical System EndoWrist® instruments. Therefore, the key objective of this work is to create miniaturised ultrasonic instruments to allow greater dexterity than conventional tools. To address this, an alternative approach can be adopted which utilises a planar folded front mass incorporated within BLT configurations with the aim to reduce the overall length of the tool whilst maintaining the amplification gain. The introduction of planar folded (PF) and twice planar folded (TPF) front masses within BLT configurations and after being optimised using design of experiments (DOE) techniques, demonstrate high amplification gains, GA = 90 @ 23 kHz and GA = 92 @ 21 kHz, respectively, and transducer lengths of 58 mm (87% length reduction) and 64 mm (86% length reduction) compared with a 450 mm Harmonic ACE®.**

I. Introduction

Ultrasonic power surgical instruments operating in the high power $10W/cm^2$ low-frequency range 20 - 60 kHz have recognised advantages, including high cut quality, fast and precise tissue cutting, less thermal damage and less bleeding [1]. With these motivations, many researchers are trying to develop ultrasonic scalpels that could interfaced with the Da Vinci® surgical system to combine the advantages of both instruments for robotic procedures. The Harmonic ACE® is the first ultrasonic actuated instrument that has been adapted with the Da Vinci® Surgical system for robotic surgery. Nevertheless, there is no existing power ultrasonic surgical instrument compatible with the Da Vinci® EndoWrist® instruments.

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The Harmonic Ace®, shown in Fig.1(a) is held on the Da Vinci® Robotic arm, to adopt and accommodate the Harmonic Ace® dimensions within the Da Vinci® environment. Thus, only longitudinal and rotational movements are allowed within this configuration, while losing the 7 degrees of freedom and dexterity of the EndoWrist instruments®. Moreover, as the device is switched on for a long period during the surgery, the shaft undergoes high wave guide stresses, that cause a high temperature raise to the shaft and tip (>200°C). Therefore, it must be controlled with high precision to prevent any undesired injuries [3] - [4].

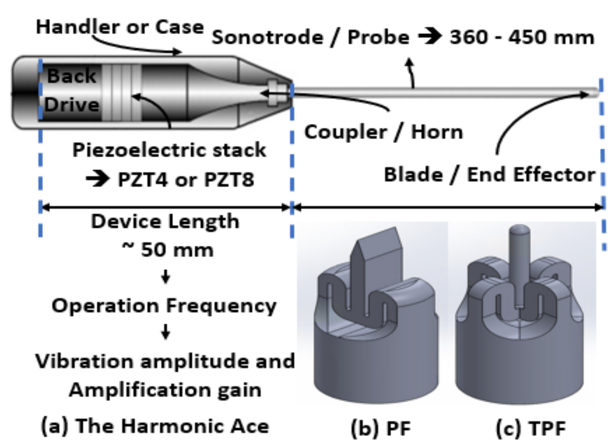

Figure 1. (a) The Harmonic Ace® internal components; (b) PF front mass which will replace the Harmonic Ace® long front mass; (c) TPF front mass which will replace the Harmonic Ace® long front mass.

Previously, Khalaji *et al.* [5] has interfaced an EndoWrist-like ultrasonic scalpel with a stepped horn. The transducer was optimised using numerical techniques about 50 kHz, compared to 55 kHz operating frequency of the Harmonic ACE®, and with 40 μm of tip vibration amplitude at 40 V_{pk} of voltage input..Furthermore, Li *et al.* [6] optimised an EndoWrist-like ultrasonic scalpel with a stepped structure front mass using finite element modelling, DOE and response surface method (RSM) and multi-objective genetic algorithm (MOGA) techniques.The optimised design generates a tip vibration amplitude about 60 μm, at 40 V_{pk}, at 55.2 kHz operating frequency, and the tip vibration amplitude could reach 135 μm at 100 V_{pk}. However, the tip temperature was not considered in both articles.

To continue developing the EndoWrist-like ultrasonic scalpel and make it more feasible to apply for future medical deployment, there is a need to increase the tip vibration amplitude and reduce the overall dimensions of the ultrasonic scalpel. To address this, a PF structure which was introduced by Sherrit *et al.* [7] has been adopted and utilised within BLT configurations. Some advantages of folded structure front masses are the adjustment of bending displacement which could improve the tip vibration amplitude and the fold thickness which provides the designer an extra degree of freedom to work on. Thus, this work is focusing on optimising the structure of both the PF and TPF design shown in Fig.1(b) and Fig.1(c), respectively. The DOE techniques with full factorial method will be used to optimise the parameters of both the PF and TPF front masses in term of maximum Amplification Gain (AG).

II. Design of EndoWrist-like ultrasonic scalpel® for Da Vinci® surgical system

In this paper we report design, simulation and optimision of an EndoWrist-like ultrasonic scalpel configured in a BLT configuration with PF and TPF front masses, using SOLIDWORKS (Dassault Systèmes, SOLIDWORKS Corp, Massachusetts, USA), finite element analysis - FEA – (Abaqus Unified FEA – SIMULIA, Dassault Systemes Vélizy-Villacoublay, France) and MODDE (Sartorius AG, Göttingen, Germany), respectively, as shown in Fig.2. These were used to study the effects of parameters including horn length, blade length, blade width and horn and blade diameter on the resonance frequency, fr, and amplification gain, AG, the latter being the ratio of the displacement amplitude of the tip to that of the back mass, to determine PF and TPF optimised designs.

Ultrasonic power surgical instruments usually operate in the high power low-frequency range 20 - 60 kHz. Thus, the DOE optimisation process should consider keeping the frequency of the transducer above the minimum ultrasonic frequency and below 60 kHz, the effective range where the transducer should still able to dissect/cauterise tissues. To address this, there were three factors studied for the PF, shown in Fig.3 and TPF, shown in Fig.4, front masses including horn length, blade length, blade width, horn thickness and blade thickness and blade diameter. The horn length and blade length were

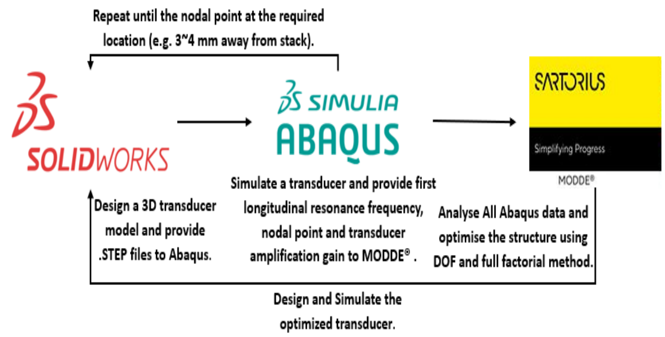

Figure 2. The design and optimisation process of EndoWrist-like ultrasonic scalpel for Da Vinci® surgical system.

designed in range between 5 and 7 mm, to always keep the resonance frequency above 20 kHz, whereas, the blade width was changed between the 1.3 and 7.3 mm (the maximum blade width possible in 10 mm diameter), maximum possible thickness for the planar folded front mass to be rigid, avoid high stress failure and to be manufacturable using Electrical Discharge Machining (EDM) and both the horn thickness and blade thickness were fixed to 1.6 mm for the PF front mass and the blade diameter of the TPF front mass was changed between the 1.2 and 1.6 mm. As there are three factors for each structure with three different parameters, considering a full factorial optimisation process, there are 27 simulations to run to be able to optimise the PF and TPF front masses.

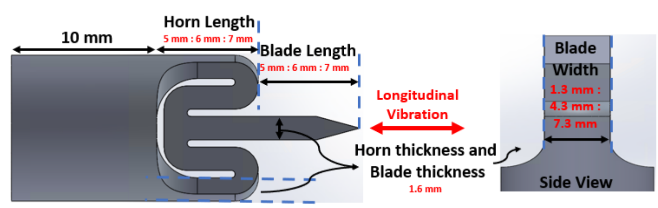

Figure 3. The investigated parameters for planar folded front mass.

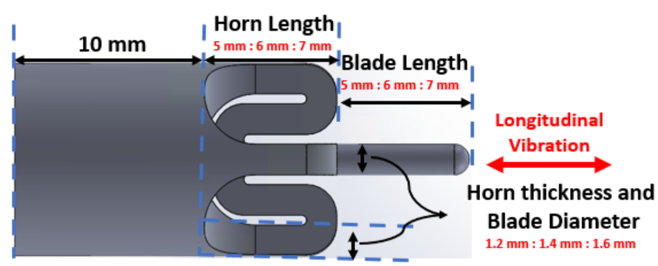

Figure 4. The investigated parameters for twice planar folded front mass.

A. Stack material, placement, vibration amplitude considerations

The piezoelectric material is the key component in any ultrasonic scalpels which convert the applied electric energy into mechanical vibration, that the front mass amplifies and transmits to the end effector/blade to cut the required tissue. As this study focuses on reducing the overall size of the ultrasonic scalpels and optimising the PF and TPF front masses incorporated in BLT configuration, hard piezoceramic PIC181 will be used through the project. The placement of piezoelectric rings between the back mass and front mass depends on the required stack vibration power and the stresses on the horn. Mathieson *et al.* [8] illustrated that the vibration amplitude and the power of the ultrasonic transducer reach the maximum possible value that the piezoelectric ring could provides when the nodal point of the transducer at the middle of the piezoelectric stack. However, the stresses are very high at the corners of the transducer's front mass, that is because the piezoceramic material has lower young's modulus than the front mass materials. Therefore, the frequency is lower when the nodal point at the middle of the piezoceramic stack, that provides higher vibration amplitude. designing the nodal points at the middle of the stack and placing the stack at the middle of the transducer, makes it difficult to design a flange at the nodal point as it is the middle of the stack. Thus, for the PF and TPF structures, it was preferable to avoid the high stress on the corners of these structures. Therefore, the nodal point was placed between 3 $\sim$ 4 mm away from Piezoelectric stack towards the front mass side.

B. Back mass dimensions and materials

As mentioned before, the back mass has a high impedance material to reduce the reverberation of the piezoelectric stack and increase the efficiency of the device. As the EndoWrist-like ultrasonic scalpels should be as short as possible, the back mass material should has high density and reasonable yield strength to maintain the nodal point 3 $\sim$ 4 mm away from the piezoelectric stack and with short back mass. Thus, the stainless steel was selected to be the material for the back mass as it has a high density, 7850 Kg/m^3, and reasonable yield strength 510 MPa. For the dimensions of the back mass, the diameter will be similar to the diameter of the front mass and piezoelectric stack, to fit the device into the 12.5 mm port that the surgeons cut when they operate a robotic surgery. The length of the back mass will be changed when the parameters of the front mass changes to always keep the nodal points of the transducer 3 $\sim$ 4 mm away from the piezoelectric stack.

III. Results and Discussions

Previously, the two planar front masses were introduced to relatively miniaturise the overall length of the ultrasonic scalpel and interface it with an EndoWrist-like manipulator. These structures were incorporated within BLT configurations with the aim to reduce the overall length of the tool whilst increasing the displacement gain. There are three factors investigated for each front mass, including horn length, blade length, blade width or blade diameter, depending on the structure. 27 virtual prototypes have been simulated for each front mass to obtain all the required results for optimisation. After the optimisation process takes place using MODDE, a 4D contour of the resonance frequency and amplification gain for each front mass were plotted and an optimised design was introduced as follows:

A. Planar folded front mass

After investigating the 3 factors of PF front mass, including horn length, blade length and blade width and simulating the 27 virtual prototypes, a 4D contour of both the resonance frequency and amplification gain could be visualised in Fig.5. As the horn length and blade length of planar front mass increases, the resonance frequency decreases, that is due to the increase of the total length of the transducer, and the amplification gain increases when the horn length increases and blade length decreases. While, when the blade width is reduced, the resonance frequency drop as the material volume of the horn drop, whereas, the amplification gain increases, as the amplification of the horn, the later is the ratio of larger diameter (outer diameter) of the horn over the blade area, is increasing when the blade width is reduced . Thus, the planar folded transducer with the longest horn length and shortest blade length and blade width, has the highest amplification gain.

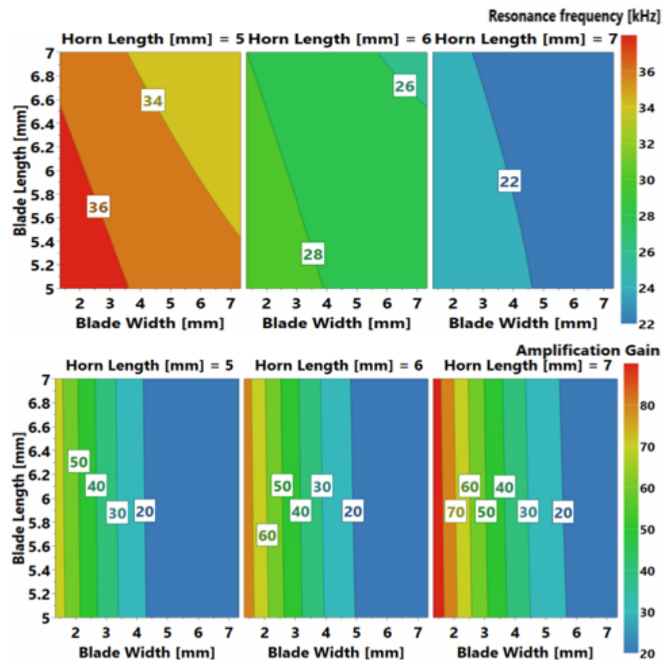

Figure 5. 4D contour represent the effect of changing the PF factor and parameters on the resonance frequency and AG of the transducer.

The optimisation software (MODDE) presented the parameters of the optimised transducer shown in Fig. 6. After simulating the BLT with optimised PF front mass parameters, the obtained results show that, the resonance frequency of the device is around 23 kHz with amplification gain about 90.The PF transducer has a lengths of 58 mm (86% length reduction) compared with a 450 mm Harmonic ACE®.

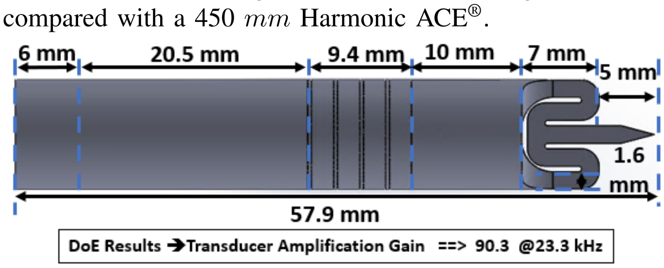

Figure 6. The optimised PF transducer.

B. Twice planar folded front mass

Similar to the PF scenario, after investigating the 3 factors of TPF front mass, a 4D contour of both the resonance frequency and amplification gain could be visualised in Fig. 7. As the horn length and blade length of planar front mass increases, the resonance frequency decreases, that is due to the increase of the total length of the transducer, and the amplification gain increases when the horn length increases and blade length decreases. While, when blade diameter is reduced, the resonance frequency drop as the material volume of the horn drop, whereas, the amplification gain increases when the blade width is reduced. Thus, the twice planar folded transducer with the longest horn length and shortest blade length and blade width, has the highest amplification gain.

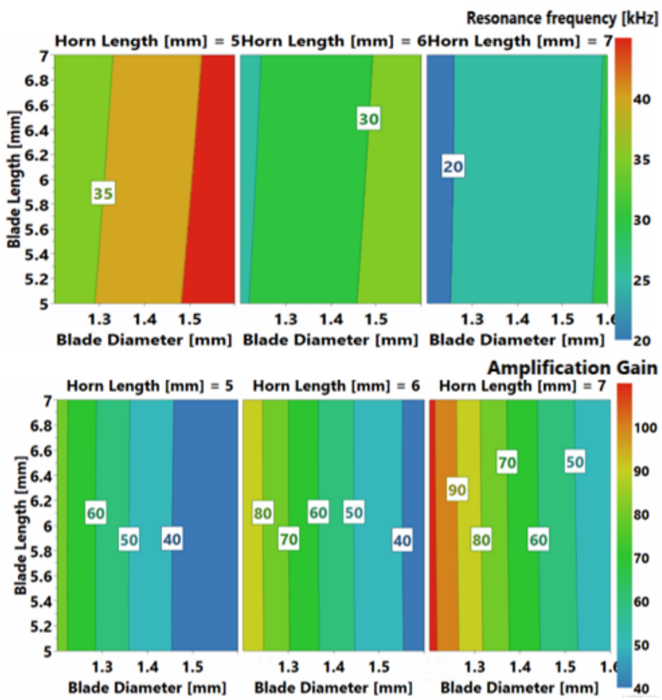

Figure 7. 4D contour represent the effect of changing the TPF factor and parameters on the resonance frequency and AG of the transducer.

The optimisation software (MODDE) presented the parameters of the optimised transducer shown in Fig. 8. The resonance frequency of the optimised TPF transducer is around 21 kHz with amplification gain about 92. The TPF transducer has a lengths of 64 mm (86% length reduction) compared with a 450 mm Harmonic ACE®.

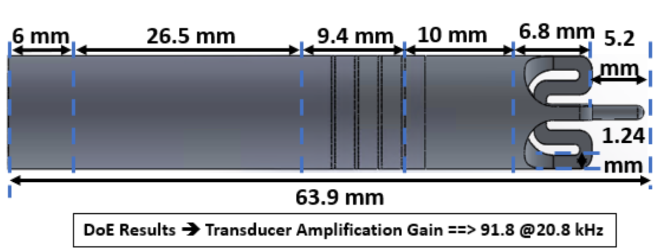

Figure 8. The optimised TPF transducer.

IV. Conclusions and Future Work

PF and TPF front masses structure have been shown to be a potential candidate to design an EndoWrist-Like ultrasonic scalpel. The optimised planar and twice planar front masses Incorporated within BLT configuration presented in section III.A and III.B, demonstrate a high amplification gain, GA = 90 @ 23 kHz and GA = 92 @ 21 kHz, respectively, and transducer lengths of 58 mm (87% length reduction) and 64 mm (86% length reduction) compared with a 450 mm Harmonic ACE®. This is attributed mainly to its smaller material volume, associated with a lower structural stiffness. For future works, The Von misses stresses on both structure will be investigated and included on the optimisation process. Both the optimised planar and twice planar transducers will be manufactured using the Electrical discharge machining (EDM) and 3D printing, respectively.

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