Development of improved ultrasonic transducers for medical surgery

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Abstract

Finite element (FE) modelling of surgical transducers has been performed and is described.

Ultrasonic transducers vibrating at around 25 kHz are used in orthopaedic surgery to cut bone. The high acoustic impedance of the metal blades used in these devices couples energy more efficiently to materials with high acoustic impedances, such as bone, whereas materials with low acoustic impedances, such as soft-tissue, are coupled weakly. Apparently, this results in preferential cutting of bone rather than soft-tissue, which can be advantageous during surgery.

The Langevin type of transducer is a common design of power transducer used in many applications, including applications in orthopaedic surgery. A Langevin transducer is essentially a solid rod that vibrates as a half-wave, longitudinal resonator with a nodal point at its centre and anti-nodes at both ends. Some designs of Langevin transducer for surgery incorporate the blade into the half-wave, longitudinal resonator, resulting in the tip of the blade being an anti-node with a large displacement. Other variants of the Langevin transducer for orthopaedic surgery have longer blade assemblies, often including horns to amplify the displacement.

It is possible to make one FE model of the main driving Langevin unit and a second FE model of the extended blade unit, including any amplifying horns. The two models of the transducer can each have their dimensions adjusted so that they have the same half-wave longitudinal resonating frequency before physical units are built and tested. The two parts can then be joined together and should work as a single unit operating as a full-wave resonator. This modular development approach has been the way that conventional ultrasonic design has progressed in the past and is still preferred if the final assembly is physically modular, say with interchangeable blade units. Alternatively, the two parts assembled as one entity can be one FE model; in this alternative approach the desired mode of longitudinal vibration can be either a half-wave or a full-wave resonator – in the latter case with anti-nodes at each end and two nodes at separate points along the length.

Results of FE models are compared for the two different approaches for developing new medical transducers: single entity or two units tuned to the same frequency. The effect of varying material properties is considered and so too is the effect of loading of the cutting edge, which results in substantial changes to the vibration modes. A change in the mode of vibration can result in a loss of cutting efficiency and increased generation of heat that can cause burning of the bone. However, certain modes of vibration, when the blade tip is locked in bone, could result in advantageous performance but require a change in driving frequency to select the new modes of vibration.

FE models have been developed in Comsol version 4.2 using the piezoelectric devices module, which incorporates both structural mechanics physics and piezoelectric physics. Solutions have been obtained using the eigen-frequency solver: to find resonant frequencies of different eigen-modes with animation used to identify the longitudinal half-wave or full-wave modes of vibration.

Introduction

The cutting of bone in surgery has for centuries been done manually by surgeons using saws, chisels and knives. A problem with saws is that they may cut into surrounding soft tissue, which is generally an undesirable side-effect. This is particularly undesirable in surgery on the spine where the spinal cord may be cut, which would almost certainly leave the patient paralysed below the position of the saw cut.

Strain-rate is a term commonly used in materials science but is less commonly used in ultrasonic technology and less frequently found with sinusoidal strain – as is the case in this application – equation 1 is appropriate.

$$Strain\ rate \leq 2\pi\ Amplitude\ x\ frequency$$

Equation 1

Bone is both strong and tough at room temperature and low strain-rates ($<10^{-6}$ s^{-1}); cutting bone is difficult due to the toughness of its long-chain collagen fibres. Bone also contains minerals. Small ultrasonically vibrating blades can be used to cut bone. Strain-rates approaching 79 s^{-1} (see equation 1) are possible using ultrasound at 25 kHz with tip displacements of 100 µm. The mechanical properties of collagen are time and temperature dependent: at low temperatures and/or high strain-rates the long-chain protein molecules in collagen cannot deform quickly enough to accommodate the applied strain and collagen behaves as a brittle material and fractures; at high temperatures and low strain-rates the collagen molecules can deform sufficiently quickly and there is no brittle fracture consequently collagen is tough – which is everyday experience. Controlled brittle fracturing of collagen is clearly advantageous while trying to cut it, consequently, the high strain-rates generated at the tip of an ultrasonic cutting tool are beneficial for cutting bone. Clearly, the higher the operating frequency and the greater the displacement of the vibrating cutting blade the more brittle fracture can be caused.

Ultrasonically activated blades are typically made of titanium metal, which has an acoustic impedance (Z_t) of 27 x 10^6 kg m^{-2} s^{-1}. The acoustic impedance of bone (Z_b) is 7.8 x 10^6 kg m^{-2} s^{-1} and the acoustic impedance of soft tissue ($Z_{s\text{-}t}$) is about 1.7 x 10^6 kg m^{-2} s^{-1}. The proportion of intensity (power/area) of ultrasound reflected (R_{12}) at the boundary between two dissimilar materials (*1* and *2*) is given by

$$R_{12} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

The proportion of intensity transmitted (T_{12}) across the boundary is

$$T_{12} = 1 - R_{12} = \frac{4Z_2Z_1}{(Z_2 + Z_1)^2}$$

Equation 1

Substituting values for acoustic impedance for ultrasound transmitted from titanium to bone gives

$$T_{tb} = 0.70$$

Substituting values for titanium and soft tissue gives

$$T_{ts-t} = 0.22$$

And

$$T_{tb}/T_{ts-t} = 3.2$$

3.2 x more power is transmitted into bone from titanium than into soft-tissue, so an ultrasonically activated knife is less likely to cause damage to soft-tissue (such as the spinal cord) than to bone.

Ultrasonic transducer design

A popular design of power ultrasonic transducer was first developed by Paul Langevin in 1916. It has a solid rod often made of titanium with an even number of coaxial piezoelectric discs sandwiched between two titanium end pieces. It has a screw running along its axis between two end pieces and through holes in the piezoelectric discs; the screw pulls the assembly together and applies a static stress to the discs – see figure 1. The static stress not only holds the assembly together (adhesives are also used) but also holds the piezoelectric discs under a static compressive stress. Many piezoelectric materials are brittle and fracture readily when placed in a state of tension but the compressive static stress prevents the piezoelectric discs from entering a state of tension and ensures that brittle fracture and failure of the transducer does not occur.

True piezoelectric materials are seldom used and polarized ferroelectric materials such as lead zirconate titanate (PZT) are used instead. PZT gives larger displacements than true piezoelectric materials for the same electric field strength. PZT is also a brittle ceramic material, so static pressure in the Langevin rod is still used. Multiple pairs of discs are used with alternating directions of polarization in a stack. The discs are wired electrically in parallel but their deformation strains add together in series. This arrangement is beneficial because lower operating voltages can be used.

When operating, the ends of the Langevin transducer move in antiphase: both ends move towards the node then both move away from the node, with the process repeated as long as electrical excitation is applied to the piezoelectric discs at the correct frequency – the frequency of natural resonance (or eigen-frequency) of the transducer. The Langevin transducer is generally operated at a frequency that has maximum longitudinal vibration level at both ends – the vibration at either end can be used to perform some form of material processing: cutting of bone in this instance.

In figure 2 results of a FE model are shown for the eigen-mode that is a longitudinal half wavelength.

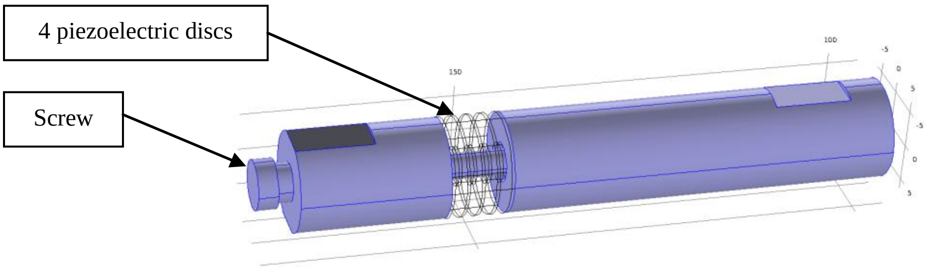

Figure 1 Drawing of a Langevin transducer with 4 piezoelectric discs (shown in wire-line outline only) and an inner screw that pulls the assembly together. The two (solid) end pieces are often made of titanium.

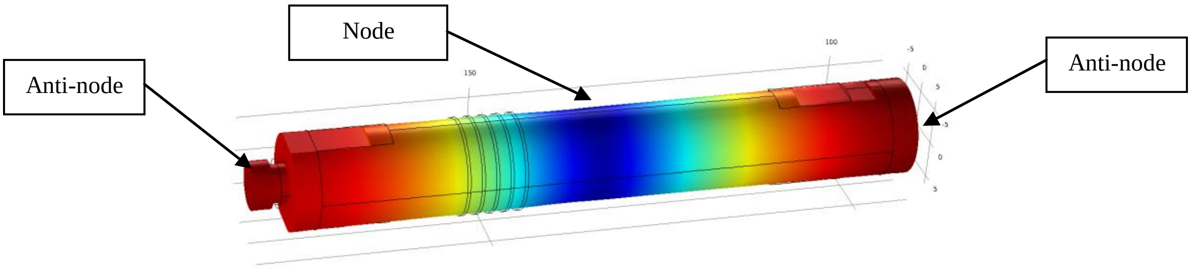

Figure 2 Eigen-frequency solution of an FE model of the Langevin transducer shown in figure 1. Colour code: blue = zero displacement, red/brown = maximum displacement. In this model the eigen-frequency is 30.9 kHz. Note the nodal (blue region) in the centre.

The nodal point in figure 2 is useful because it is the best location for making a mechanical support for the transducer (support not shown in either figures 1 or 2). Results of eigen-frequency analysis of FE models reveals many resonances and it is necessary to display each eigen-mode in order to find the longitudinal half-wave vibration pattern. Other modes have torsional and flexural components not normally used for cutting bone.

Transducers for orthopaedic surgery

Figures 3 and 4 show a FE model of an orthopaedic transducer. This is an example in which the Langevin source of ultrasound and the blade are integrated into a single half-wave resonator. The design also incorporates a tapering horn which performs two desirable functions: it magnifies the mechanical displacement in the blade and presents a smaller cross-sectional area to penetrate into the bone – the latter point makes cutting much easier.

The electrical wiring of the piezoelectric discs must be covered by insulation to prevent electrocution of the surgeon and patient. A plastic enclosure can be attached to the support plate to cover the electrical wiring. The enclosure can also be used by the surgeon to hold the device and to manipulate it during surgery.

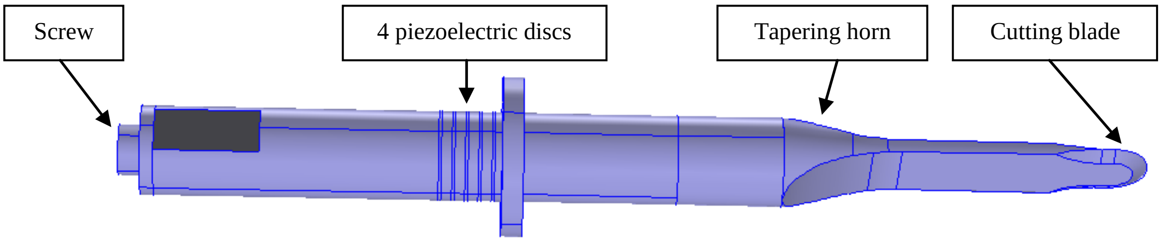

Figure 3 FE model (study stage before meshing and solving) of an orthopaedic transducer based upon a Langevin design but with a blade at one end and a mounting plate at the point.

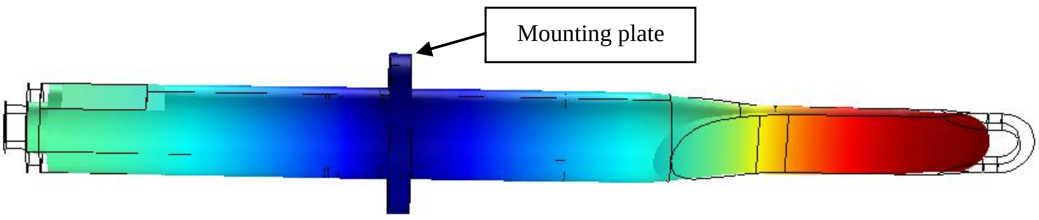

Figure 4 Results of FE model after solving for eigen-frequencies. This is the longitudinal half-wave resonance mode at 21910 Hz. The normal (un-displaced) position of the components is shown in wireframe outline. Colour code: blue = zero total displacement; red/brown = maximum total displacement. Note the mounting plate is at the nodal point (blue). Maximum total displacement (brown/red) is at the tip of the cutting blade (as desired). Actual displacements are magnified in the figure.

Figure 4 shows the result of solving the FE study using an eigen-frequency solver. One resonance (eigenmode) is illustrated in figure 4: it is the longitudinal half-wave resonance mode at 21910 Hz. This mode produces piston-like motion of the cutting tip and is believed to be best suited to cutting bone. Animation of the mode reveals the piston-like motion. **T**he tapering horn causes a larger total displacement in the blade than at the other free end of the device –demonstrating displacement amplification created by the horn due to reduced cross-sectional area of the cutting blade.

FE models can be used to optimize performance of transducers by: (a) positioning the support plate precisely in the middle of the nodal point and (b) verifying the gain in displacement achieved by the horn that narrows from the circular Langevin rod down into the blade that is in contact with bone (c) determining the optimum frequency of vibration to cause a longitudinal resonance. Experiments with an identical transducer confirmed that FE predictions for the ideal resonating frequency were accurate.

Cutting bone

Bone consists of: (a) a hard external material, called cortical bone, that provides most of the mechanical strength of bones and (b) an inner softer, spongy material, called trabeculae bone in the medullary cavity. The hard outer material is made up of lamellae fibres aligned parallel to the major axis of the bone. The outer cortical bone being hard would normally be more difficult to cut but experiments show that ultrasonic transducers are able to cut the cortical bone relatively easily, which may be due to high acoustic transmission between transducer and cortical bone (see equation 1) or it may due to greater sensitivity to fracturing of cortical bone at high strain-rates.

Paradoxically, once an ultrasonic transducer has cut relatively easily through the hard and normally tough cortical outer shell it then becomes more difficult to proceed deeper into the softer trabeculae, which may be due to: (a) the lower acoustic transmission, or (b) that trabeculae bone is less likely to fracture at high strain-rates or (c) transducer blades generally thicken with greater penetration and so become trapped by the cortical bone (d) the ultrasonic transducer is no longer able to resonate in a longitudinal half-wave eigen-mode if the driving frequency is kept constant. When the blade is trapped it is observed that heat is generated in the contact zone between bone and transducer blade and burning and smoke are observed. These are undesirable effects.

FE models have shown that a contributing factor to the poor cutting is that the boundary conditions on the transducer are altered by significant penetration of the blade into bone and this alters the mode in which the transducer vibrates. One of the principles of operation of a Langevin transducer is that the rod vibrates in a half-wave longitudinal mode, so that the blade end is moving axially in a piston-like motion, which is believed to maximize cutting. The FE model assumes free motion at each end of the Langevin rod but when the blade end is trapped in cortical bone it is no longer free to move. FE models have been developed to model trapping of the blade in bone. The models are crude in their representation of bone: no internal medullary structure is present and it is assumed that the bone is isotropic in material properties but the results are illuminating nonetheless.

The model shown in figure 4 was modified to add a cylinder with a diameter (50 mm) representative of large bones but with a limited length (100 mm); the flat ends of the cylinder were made fixed to represent extended length. Values of material properties were taken from Burr et al[1] except that the bone was given the value of its transverse Young’s modulus. Isotropic damping was applied to the bone cylinder with damping factor $\eta = 1$.

The most important result of the FE model was that there was no longer a longitudinal half-wave eigen-mode at 21910 Hz. If the transducer is only ever operated at one frequency, in this case 21910 Hz, then the transducer will not function well once the blade becomes locked in the outer cortical because the critical vibrating node no longer exists. However, there other modes that appear when the blade is locked and these modes may be of use but to access them requires a change in driving frequency of the electrical oscillation applied to the piezoelectric discs.

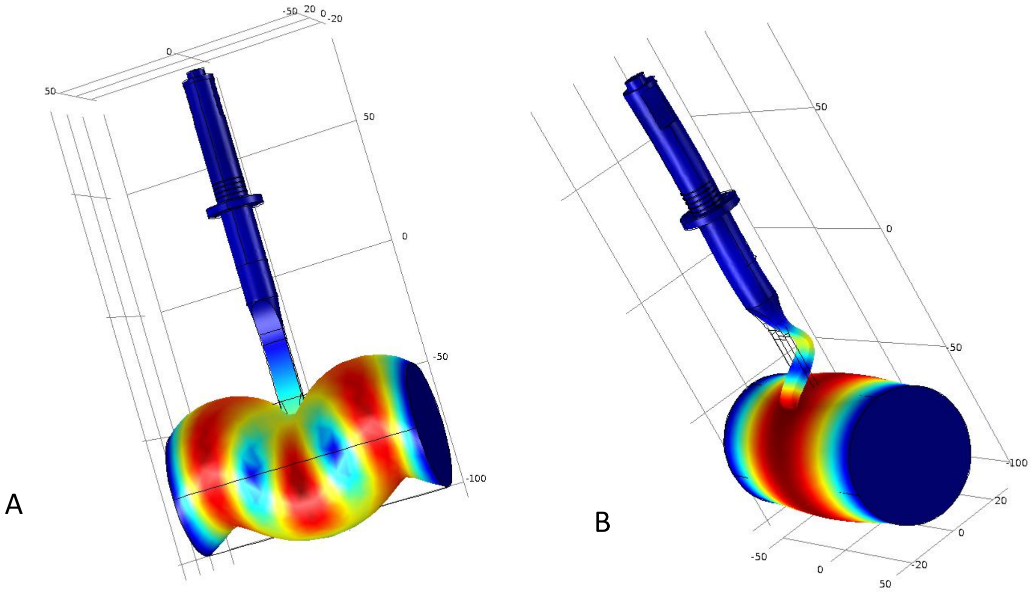

Figure 5 Transducer used in FE model for figure 4 but with a cylinder of bone into which the tip of the blade is embedded. The embedded end of the blade imposes a new boundary condition and the modes of vibration are altered substantially. The original cutting mode at 21910 disappears. Two modes that might be of use in surgery are shown: A – the transducer in a quarter-wave longitudinal resonance mode (27716 Hz) coupling strongly into the bone so cutting may be achieved; note the nodal mounting point is maintained; B – the blade is in a transverse flexural mode and the bone is also oscillating in a torsional mode – this may be useful for freeing the blade from the bone. The mounting point is also a node in this mode. Actual displacements are magnified in the figure.

It may be desirable for a novel orthopaedic ultrasonic cutting device to use other accessible modes (by changing the operating frequency) instead of continuing with little or no chance of success to try to start the longitudinal half-wave resonance at the original cutting frequency when the blade is embedded in the cortical bone. Other modes include flexural (see figure 5 B) and torsional movement of the blades that may help to free the blade or there are other longitudinal modes that couple strongly into bone (see figure 5 A) that may allow cutting to proceed. These have not been tried in tests so far. It is possible that the longitudinal strains created by the piezoelectric discs do not couple well into transverse eigenmodes; experiments are recommended to determine how effective excitation will be.

Another practical approach would be to use a modular transducer with a slightly wider blade for cutting into cortical bone then change to a thinner blade for cutting trabeculae bone. Alternatively, the surgeon could use one blade and make an initial opening in the cortical bone that was large enough so that the blade would not become jammed when it was used to cut deeper into trabeculae bone.

Modular transducer design

Traditionally, power ultrasonic transducers have been modular in design with a Langevin engine resonating at a half-wave longitudinal resonance at an eigen-frequency of f_e. It would be joined to a material processing device (a blade in this case). The processing device would also be a resonator of some type, say another half-wave resonator, that resonates at exactly the same frequency, f_e, as the Langevin engine. The two parts would be developed separately and each tuned to the same frequency, f_e. When joined together the composite unit should also resonate at a frequency of f_e but in a full-wave eigen-mode. The reason for this approach was the difficulty, before reliable FE methods, of designing a single integrated unit.

To illustrate the approach the transducer already shown in figures 3, 4 and 5 will be used but in a modified form. The FE model was split into three different models: (a) the Langevin engine only, (b) the blade assembly only and (c) the recombination of parts (a) and (b). The FE model was primarily made from primitive geometrical units, such as cylinders, using parameterized dimensions. By means of changing parameters it was relatively straightforward to modify geometries. In creating final models for (a) and (b) above there were four main constraints:

1. Maintain the overall appearance of the transducer: do not change diameters, piezoelectric parts, screws or nuts.
2. Select the same operating frequency, f_e, to be the half-wave longitudinal resonance of both parts (a) and (b) above.
3. Ensure that the mounting plate was positioned at a node (no vibration).
4. Only change the lengths of two components of the transducer: (i) the length of the end piece next to the torque nut on the Langevin engine and (ii) the length of a spacer between the blade and the Langevin engine.

Results are shown in the following figure.

The method represents the traditional method of developing an ultrasonic power transducer. One of the disadvantages of this method is that it results in composite transducers that are longer than they need be (compare figure 6 C, which is about 200 mm long, with figures 4 and 5, the same transducer, which is only 150 mm long). The composite transducer in figure 6 C has two nodes, either or both of which could be used for mounting or holding the transducer.

It is interesting that the full-wave resonant frequency of figure 6 C is 29461 Hz which is 2% greater than 28906 Hz of its two component parts. This is almost certainly due to the torque screw, which probably provides little or no stiffening of the Langevin engine (figure 6 A) but does provide stiffening of the composite transducer (figure 6 C).

The great advantage of the modular transducer design is that it allows interchangeable blades to be used on the same Langevin engine.

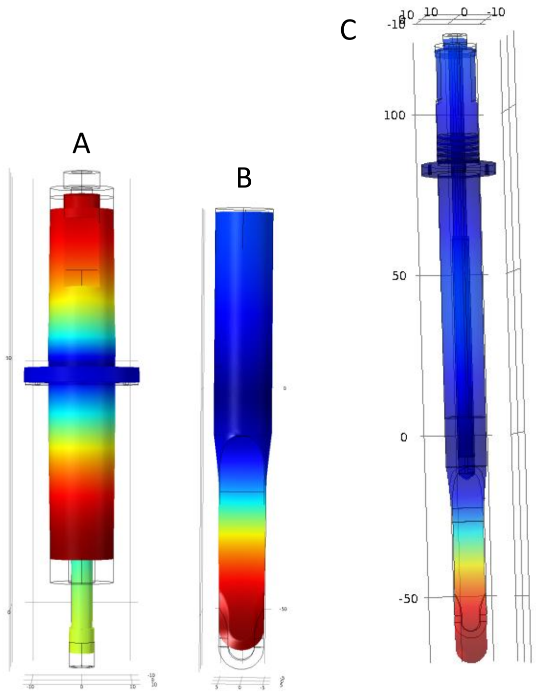

Figure 6 Transducer used in FE model for figures 3, 4 and 5 but modified and split into two parts in A and B. The resonant frequency of both A and B is 28906 Hz (both in half-wave longitudinal mode) and for C it is 29461 Hz (in full-wave longitudinal mode). In A and B there is only one node for each FE model (dark blue) and the mounting plate in A is situated on the node. In C there are two nodes because the composite unit operates in a full-wave mode. Actual displacements are magnified in the figure.

Varying material properties

Titanium is supplied in various alloys, often with small quantities of aluminium or vanadium at 6% or 4% and most forms of titanium have dissolved oxygen. Titanium is generally supplied as its β-phase, a body centred cubic crystal structure, which is ductile and malleable so that machining is possible, with additives to stabilize it. In the absence of β-phase stabilizers, the β-phase can be converted by heat treatment to the α-phase (hexagonal close packed crystal structure) which is harder and less ductile. Therefore, Titanium can be formed into shape in the β-phase then converted to the stronger α-phase by heat treatment – thereby preserving the shape imparted in the β-phase. This is a substantial advantage for titanium making it workable but ultimately strong and hard. This also means that titanium has varying material properties.

Four different sources of material properties have been used in FE models (for example Kaye and Laby[2]) of the transducer shown in figures 3, 4 and 5. No dimensional changes have been made and all other components have used unvarying material properties. It is probable that all four sets of material properties relate to β-phase titanium and one at least is known to be an alloy. Data had ranges of: 2% in density values, 6% range in Young's modulus and 6% range in Poisson's ratio.

The four FE models predict eigen-values for the longitudinal half-wave resonance mode of between 22140 Hz and 20333 Hz – a range of about 9%. The position of the mounting plate remained on the node for all data and was therefore unaffected by variations in material properties. Provided electronic equipment used to drive these transducers is capable of adapting the drive frequency to match the eigen-frequency of the longitudinal half-wave resonance then there should be no particular problem with the variation in material properties for the β-phase of titanium.

However, no material properties were found for pure α-phase titanium and the use of this phase of titanium may result in substantially different eigen-frequencies.

Conclusions

FE modelling in Comsol 4.2 of surgical transducers is effective in the development of novel transducers for cutting bone. The Langevin type of transducer excites longitudinal vibrations, with large amplitudes generated in the half-wave eigenmode. It is possible to make one FE model of the main driving Langevin engine and a second FE model of the extended blade unit. The two FE models of the transducer can each have their dimensions adjusted so that they have the same half-wave longitudinal resonating frequency before physical units are built and tested. Alternatively, a single FE model can be used for a single, composite entity. Single entity transducers are generally smaller in size than two units joined together. However, two units can be modular, allowing interchangeable blades for example, which may be an advantage in some applications.

The effect of loading on the cutting edge, embedding the blade in cortical bone for example, prevents the Langevin transducer from resonating in its longitudinal half-wave eigenmode resulting in no cutting and undesirable generation of heat. However, by changing the frequency of the electrical excitation applied to the piezoelectric discs in the Langevin engine, different eigenmodes of vibration can be excited resulting in potentially advantageous performance, for example: loosening a jammed blade or restarting cutting.

The effect of varying material properties, using four different sources of values, shows that there is a 9% range of eigen-frequencies, which should not pose a problem practically. However, these results only apply to the commoner β-phase of titanium and the commonest of titanium alloys.

Acknowledgements

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2. Kaye G. W. C., Laby T. H., "Tables of physical and chemical constants" 15th Ed. (1986) Longman, England.