Characterisation of commercial and prototype power ultrasonic devices used in bone surgery

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Piezosurgery® Device

Image courtesy of Mectron S.p.A

Developed and manufactured by Mectron S.p.A
Piezosurgery® Device: Vibrational behaviour

Mectron dental transducer with OT7 insert
Ultrasonic bone cutting: Benefits

- Reduced applied loads
- Reduced debris formation
- Increased accuracy
- Low threat to delicate soft tissue; nerve, brain & spine
- Requires 20-30% of force compared to traditional cutting devices
- Fine debris compared to burs and saws
- Enhanced healing time
- Less likely to damage tissue which could lead to halting the procedure
Device precision

Photron fastcam ultima APX

Recording: Frame rate: 4000fps Resolution: 512x512
Video: Frame rate 1000fps

Window cut in egg

Mectron transducer with OT7 cutting insert
Clinical procedure: Bilateral sagittal split

Osteotomy of the mandibular
Shortens or lengthening of the lower jaw to correct dentalfacial deformities caused by congenital abnormal skeletal development as well as trauma sequelea.

Mandible exhibiting prognathism

Normal mandible position

Mandible exhibiting retrognathism
Clinical procedures: Osteotomy

Comparison with traditional cutting methods

Representative histologic photomicrographs of decalcified specimens characterising the appearance of the cut edges of osteotomy incisions baseline (original magnification 2.5x, stain hematoxylin-eosin)

Images courtesy of Mectron S.p.A

**Bone saw**

**Bone bur**

**Ultrasonic device** (Piezosurgery® Device)
However, power ultrasonic devices can exhibit behaviour that reduces their performance and which can subsequently lead to premature device failure.

Aim of Research
To create design criteria for stable power ultrasonic systems through understanding sources and causes of nonlinear behaviour
Poor performance in power ultrasonic devices

Poor performance and reliability can stem from a number of sources, such as;

• Sub-optimised / poor design
• Modal coupling
• Modal interaction
• Presence of Duffing-like behaviour
Outcome of poor reliability and performance

Failure of cutting blades
Linear response of ultrasonic devices

Amplitude of vibration is proportional to input excitation.

Measurements

Excitation at individual frequencies

Continuous / burst swept sine wave

Low excitation levels
Nonlinear responses of ultrasonic devices
Can significantly influence driving stability as well as hindering power ultrasonic system development

Nonlinear behaviour

Frequency Shifts
Softening / Hardening effect

Amplitude

软ening Liner Hardening

Frequency

$\omega_n$
Nonlinear responses of ultrasonic devices

Can significantly influence driving stability as well as hindering power ultrasonic system development

Nonlinear behaviour

Frequency Shifts
  Softening / Hardening effect

Bifurcations
Nonlinear responses of ultrasonic devices

Can significantly influence driving stability as well as hindering power ultrasonic system development

**Nonlinear behaviour**

- Frequency Shifts
  - Softening / Hardening effect
- Bifurcations
- Jump-resonance hysteresis
Nonlinear responses of ultrasonic devices

Nonlinear behaviour in piezoceramics is influenced by:

Application of high stresses
  • High vibration amplitudes

Dielectric, mechanical and piezoelectric losses within piezoceramics
  • Temperature increases
  • High electric field

Ultrasonic tools:

Application of high stresses
  • High vibration amplitudes

Device architecture
Material selection
Influence of temperature and $\varepsilon$ on piezoceramics

Piezoceramic samples:

$Q_m$ values:

#A: 60.7, #B: 85.2
#E: 1554, #N: 1292, #C: 2053

Umeda et al., 1999.
Influence of temp and $\varepsilon$ on acoustic efficient metals

Campos-Pozuelo & Gallego-Juárez, 1996.

<table>
<thead>
<tr>
<th>Material</th>
<th>Limiting strain</th>
<th>Max Stress w/o fatigue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duraluminium</td>
<td>$2.4 \times 10^{-4}$</td>
<td>30MPa</td>
</tr>
<tr>
<td>Titanium</td>
<td>$2.2 \times 10^{-3}$</td>
<td>200MPa</td>
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</tbody>
</table>

Attenuation with respect to strain

T = 42°C

T = 23°C
Characterisation of ultrasonic devices

Experimental modal analysis

• Low power excitation: linear region of vibration
• Resonant frequencies and mode shapes extracted

Harmonic excitation

• Both low and high power excitation: linear and nonlinear regions
• Excitation via a bidirectional sweep
• To understand nonlinear characteristics of the ultrasonic device it is necessary to remove thermal contributions from the piezoceramics
Characterising of power ultrasonic devices

Experimental modal analysis (EMA)
Harmonic excitation

Bidirectional burst sine sweep technique

- 6000 cycles
- At 28kHz; 0.286 sec
- Time delay; 1-10 sec
Investigated Devices

OT7

BI

Mectron Transducer
EMA: Half wavelength devices

OT7: $f = 27190\text{Hz}$

BI: $f = 28761\text{Hz}$
EMA: Half wavelength devices

(i) Longitudinal Node

(ii) Flexural Node

OT7: $f = 27190\text{Hz}$

(i) Longitudinal Node

(ii) Flexural Node

BI: $f = 28761\text{Hz}$
EMA: Full wavelength devices

$I_1$: $f = 25935\text{Hz}$

$I_2$: $= 28627\text{Hz}$
EMA: Full wavelength devices

I1: f = 25935Hz

I2: f = 28627Hz
Influence of elevated piezoceramic temperature

I3 insert
Time delay: 1sec

Time delay: 10sec
Influence of elevated piezoceramic temperature

Duffing-like behaviour

Resonant frequency shift

Hysteretic width

Amplitude (microns)

Frequency Shift (Hz)

Hysteretic Width (Hz)
Harmonic characterisation

OT7

I1

I3

B1

I2

I4
Harmonic characterisation

Resonant frequency shift

- OT7: Up
- OT7: Down
- BI: Up
- BI: Down
- I1: Up
- I1: Down
- I2: Up
- I2: Down
- I3: Up
- I3: Down
- I4: Up
- I4: Down

Resonant frequency shift at 2.5μm (Hz)

<table>
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<tr>
<th></th>
<th>Resonant frequency shift at 2.5μm (Hz)</th>
<th>Amplitude jumps</th>
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<tr>
<td></td>
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<td>Amplitude (μm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Voltage (Vrms)</td>
</tr>
<tr>
<td>OT7</td>
<td>121</td>
<td>1.81</td>
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<tr>
<td></td>
<td></td>
<td>15</td>
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<tr>
<td>BI</td>
<td>133</td>
<td>1.81</td>
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<td>15</td>
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<tr>
<td>I1</td>
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<td>1.97</td>
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Harmonic characterisation

Hysteretic width

<table>
<thead>
<tr>
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<th>Hysteretic region at 2.5μm (Hz)</th>
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<tbody>
<tr>
<td>OT7</td>
<td>12</td>
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<tr>
<td>BI</td>
<td>8</td>
</tr>
<tr>
<td>I1</td>
<td>6</td>
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<tr>
<td>I2</td>
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<tr>
<td>I3</td>
<td>2</td>
</tr>
<tr>
<td>I4</td>
<td>8</td>
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</table>
Power harmonic characterisation: Spectral response

OT7

I1

BI

I2
Findings

- Good correlation of resonant frequencies and longitudinal mode shapes between FEA and EMA.
- Devices operating with elevated PZT temperatures exhibited increased levels of nonlinear behaviour;
  - Increase frequency shifts
  - Larger hysteresis regions
  - Experimental method of significantly reduced thermal effect
- Devices operating at elevated amplitudes of vibration exhibited increased levels of nonlinear behaviour;
  - Increase frequency shifts found in $\frac{1}{2}\lambda$ devices (lower $Q_m$ & higher strains)
  - Hysteretic regions increase with amplitude of vibration – Geometry appears not to influence this behaviour
- Inserts containing blade tip in both (OT7) $\frac{1}{2}\lambda$ & (I1) full $\lambda$ assemblies induce flexural motion that increases the spectral response;
  - Possibility of a “route to chaos”
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EPSRC lone pool: High speed camera

Graphics
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Thank you for listening

Questions?
References

www.mectron.com


