ASSESSMENT OF TITANIUM WIRE AS AN ENDOSCOPIC SURGICAL TOOL

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ABSTRACT

During scientific-research programmes in the Republic of Croatia, a possibility to apply high-power ultrasonic point sources for minimally invasive neurosurgery has been noticed. Earlier experiences with applications of high energy ultrasound have induced the idea of ultrasonic energy transfer through an elastic wire waveguide. The scope of this study is to present the results of theoretical and experimental research in the field of generation and propagation of high-power ultrasound along the titanium wire as an endoscopic surgical tool. On the basis of theoretical calculations for generation and transmission of ultrasonic waves from the ultrasonic transducer, through the mechanical concentrator to the endoscopic tool, trimming to different surgical applications has been described. In the experimental part, methods for verification of theoretical results have been presented. This includes methods for validation the performance of the 1.6 mm titanium wire as an endoscopic tool and experimental methods for assessment of electric and acoustic characteristics.

1. INTRODUCTION

Contact ultrasonic surgical systems are widely used since late 1970-ies, but requirements on minimally invasive surgical procedures have placed new demands to attachment tool dimensions of the surgical equipment. In contact ultrasonic surgical systems, endoscopic tools are commonly produced in two ways:

- As a long concentrator of mechanical energy, having length equal to the multiple integer of the half-wavelength, i.e. \( n \lambda/2 \).

- In certain cardiosurgical [1, 2, 3, 4], neurosurgical [5, 6], urological [7] applications, the length of the endoscopic tool of \( l \approx 900 \text{ mm} \) and diameter less then 2 mm is needed. That requirement may be fulfilled only if the waveguide is manufactured from appropriate materials shaped as thin, long rods that enable transfer of the ultrasonic waves. Usually a metal wire is the choice, although in some experimental cases use of optical fibres have been reported [8].
An endoscopic tool of arbitrary shape should ensure efficient transfer of mechanical energy from the ultrasonic transducer to the medium where the operation takes place, by amplifying and concentrating it in a specially shaped mechanical concentrator. The complete system has an operating frequency $f$, so the dimension of the sandwiched ultrasonic transducer is equal to $\lambda/2$, while the mechanical concentrator and the endoscopic tool have a length equal to the multiple integer of the half-wavelength ($n\lambda/2$; $n = 0,1,2,..$). Usually the endoscopic tool is manufactured in the shape of a thin waveguide with constant cross-section $S$ and unit factor of magnification, $M$. Successful use of metal wires for transfer of ultrasonic energy has been confirmed in several applications [9, 10, 11, 12]. The most important advantages of using metal wire as an endoscopic tool are:

- The metal wire ensures transfer of ultrasonic energy with a satisfactory efficiency coefficient [13].
- Mechanical energy can be concentrated to the distal end of the endoscopic tool, so directivity of the ultrasonic intensity is accomplished [14].
- During the transfer through the waveguide, the mechanical energy is not transferred to narrow zones [13].
- For waveguides in “free vibration” mode (i.e. without a rigid enclosure), no significant loss of mechanical energy has been reported [12, 13, 14].

For endoscopic tools of arbitrary shape theoretical analysis of the tool vibration, with certain limitations, shows that in contact ultrasonic surgical systems for minimally invasive surgery longitudinal and transverse waves occur when harmonic excitation is applied.

2. MEASUREMENT OF THE ELECTROACOUSTICAL PARAMETERS OF THE TITANIUM WIRE SURGICAL TOOL

Using an endoscopic tool in the form of a metal waveguide (wire) presumes longitudinal mode of vibration, while the transverse mode occurs due to possible wire bending or operation in an extremely nonlinear mode. The theoretical wave-length of the endoscopic tool at the operating frequency can be calculated by using the sound speed correction due to wire diameter, with known Young elasticity modulus and specific density of the material, ($n\lambda/2;n=0, 1, 2,...$), (Table 1.). In order to achieve the highest electroacoustic efficiency $\eta_{ea}$ of the probe experimental determination of the tool length for each unique surgical application is necessary. For this purpose the method of mechanical resonance measurement has been used. In contrast to theoretical requirements, the shaped mechanical concentrator is manufactured in such a manner that the resonance frequency of the basic longitudinal mode ($n = 1$) is higher than the operating frequency $f_r$ of the ultrasonic transducer for given $\Delta f$. The experiment shows that for the ultrasonic transducer operating frequency of approx. $f_r = 24800$ Hz, the frequency difference $\Delta f$ must be must be around 3500 Hz to 4000 Hz. The mechanical concentrator manufactured in such way is slightly shorter than the tuned concentrator for the resonance frequency of the ultrasonic transducer. Characterization of such a mechanical subsystem by means of electrical input impedance measurement is shown in Fig. 1. This intentional shortening of the concentrator is compensated by an appropriate matching element for transfer of vibration from the mechanical concentrator to the endoscopic tool. The length of the matching element, $l_{PE}$ is calculated according to

$$l_{UZP} + l_{KME} + l_{PE} = n\frac{\lambda}{2}$$

(1)
where: \( l_{UZP} \) - length of the ultrasonic transducer
\( l_{KME} \) - length of the mechanical energy concentrator

If the shape and dimension of the subsystem (mechanical concentrator and endoscopic tool) satisfies (1), the measured resonance frequency \( f_r \) is equal to the resonance frequency \( f_r \) of the ultrasonic transducer.

Further iteration of the procedure gives the change of the endoscopic tool length around the expected (theoretic) length value. The resonance frequency of the endoscopic tool \( f_{r,e} \) corresponds to the resonance frequency of ultrasonic transducer \( f_r \) only if following condition is satisfied:

\[
l_{UZP} + l_{KME} + l_{PE} + l_{EN} = n \frac{\lambda}{2}
\]

(2)

where: \( l_{EN} \) - endoscopic tool length

The obtained resonance frequency of the whole system (sandwiched ultrasonic transducer + concentrator of the mechanical energy + matching element + endoscopic tool) must correspond to the resonant frequency of the ultrasonic power generator. The advantage of this method is that measurement results show all vibration modes of the complete ultrasonic probe (Fig. 2 and 3). During verification of the ultrasonic probe NECUP-2 with titanium wire as the endoscopic tool the start length was 906 mm, with an iteration step of 10 mm. In the vicinity of the expected resonance frequencies the iteration step has been downsized to 1 mm. After each shortening of the endoscopic tool, validity of (2) has been verified by means of measurement the input electric impedance of the whole mechanical system.
Table 1. Experimental determination of the endoscopic tool length for the frequency $f = 24.8\, \text{kHz}$

<table>
<thead>
<tr>
<th>$l/(n\lambda/2)$</th>
<th>$\lambda/2$</th>
<th>$\lambda$</th>
<th>$3\lambda/2$</th>
<th>$2\lambda$</th>
<th>$5\lambda/2$</th>
<th>$3\lambda$</th>
<th>$7\lambda/2$</th>
<th>$4\lambda$</th>
<th>$9\lambda/2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n\lambda/2$, (mm) (calculated)</td>
<td>98,1</td>
<td>196,2</td>
<td>294,3</td>
<td>392,4</td>
<td>490,5</td>
<td>588,7</td>
<td>686,8</td>
<td>784,9</td>
<td>882,99</td>
</tr>
<tr>
<td>$l$, (mm)</td>
<td>98</td>
<td>195</td>
<td>293</td>
<td>392</td>
<td>489</td>
<td>588</td>
<td>686</td>
<td>784</td>
<td>883</td>
</tr>
<tr>
<td>$\Delta f / \Delta l$, (Hz/mm)</td>
<td>42</td>
<td>40</td>
<td>30</td>
<td>28</td>
<td>24</td>
<td>22</td>
<td>20</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>$\eta_{ea}$, (%)</td>
<td>34</td>
<td>37</td>
<td>38</td>
<td>39</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>35</td>
<td>32</td>
</tr>
<tr>
<td>$\Delta$, (mm)</td>
<td>0,11</td>
<td>1,2</td>
<td>1,3</td>
<td>0,4</td>
<td>1,5</td>
<td>0,7</td>
<td>0,8</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$\Delta$, (%)</td>
<td>0,11</td>
<td>0,61</td>
<td>0,44</td>
<td>0,1</td>
<td>0,3</td>
<td>0,11</td>
<td>0,11</td>
<td>0,13</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2. Summary presentation of 320 measurements of ultrasonic probe NECUP-2 mechanical resonances with endoscopic tool having length equal to 0 mm to 906 mm

By marking curve $f = 24800\, \text{Hz}$ on Fig. 3 and crossing that curve with family of curves that represent occurrence of resonances, gives the area of possible useful applications (Fig. 4). In the frequency range of 10 kHz to 40 kHz useful application of the basic longitudinal mode is possible with 9 different lengths of the endoscopic tool. Around the basic vibration mode of the system having length of the endoscopic tool equal to 98 mm shortening of the endoscopic tool by 1 mm causes shifting of the resonance frequency of the whole system by 42 Hz.
Figure 3. Summary presentation of positions of the ultrasonic probe NECUP-2 mechanical resonances with endoscopic tool length equal to 0 mm to 906 mm

Figure 4. The dependence of the resonance frequency of the ultrasonic probe NECUP-2 on endoscopic tool length for 9 possible applications
In similar way for an ultrasonic system having the endoscopic tool 883 mm long, shortening of the tool by 1 mm causes a shift in the resonance frequency of 17 Hz. The deviation from the theoretically determined value of the endoscopic tool length, for any application, does not exceed 1 %. It is necessary to emphasize that electroacoustic efficiency of the ultrasonic probe NECUP-2, for each of the possible 9 applications is (35 ± 4) %, which confirms wide applicability of the titanium wire endoscopic tool in different surgical procedures.

4. REFERENCES