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NUMERICAL/EXPERIMENTAL CHARACTERIZATION OF A PIEZOELECTRIC DRIVEN ELECTROMEDICAL DEVICE

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Abstract

The present work refers to the numerical/experimental characterisation of an electromedical device, based on piezo actuator technologies, used for dermacosmetic applications.
Special focus was given to the fatigue related problems that have arisen during the operational life of the device, and which are related to the high frequency dynamic loads to which the device itself is subjected.
Preliminary studies have indicated a recursive crack faults that characterize, the slim extremities of the devices (bar); previous test, also put in evidence, that the crack location generally lies along an operational deflection mode nodal line.
To better understand the physical phenomena at the basis of this circumstance and to design specific solutions to overcome this problem, a set of numerical and experimental activities have been planned and performed.
The set of activities may be summarised as follow:

- FEM modelling of the bar devices and extraction of eigen-frequencies and modes
- FEM modelling of forced response to the piezoelectric excitation and the calculation of fatigue parameters
- Experimental vibrational analysis by the use of scanning laser technique; operational mode shapes extraction.

It should be noted that the use of the laser technique has permitted the identification of the high frequency modes and has avoided problems which could arise with accelerometers due to their dimensions, mass loading effects and limited frequency response.
The results of this program have shown good agreement between the experimental and numerical values and have identified also the significant influence of the boundary conditions on the life on the bar.
The study has also identified some possible solutions including the modification of the material, change of shape, or the use of a different soldering technology [1] [2].

1. INTRODUCTION

Skin Master Plus is a revolutionary tool for skin rejuvenation combining three technologies; it removes superficial skin layers and regenerates deep ones, makes face smoother and brighter just from the first treatment. Ultrasound low frequency peeling removes dead cells, excess of sebum, make-up residues and other harmful substances, such as the polluting agents in the air. Through skin cleaning it is easy to achieve a perfect and healthy exogenous moisturization, using Skin Master Plus together with specific solutions. Modulated Lotti Micro-Currents (MLM) represents a powerful metabolism activator and carries out an effective rejuvenation action, preventing wrinkles. Skin structures compression and decompression achieve extraordinary skin permeability and an effective hyperaemia, improving nutritive elements supply and absorption (sonophoresis), thanks to micro-massage and cavitation effect, attained by low frequency ultrasounds. Micro-currents, transmitted by microelectrodes, create an exudative skin reaction, causing fibroblasts proliferation. Fibroblasts synthesize collagen and elastine. This way body itself produces collagen and skin regains resistance and suppleness with a selective and enduring action even on deep wrinkles. Skin Master Plus avails itself of Biorêve dermo-cosmetic products, devised to extend treatment effects, to regenerate skin vital needs and to provide for physiologic lacks. The scope of this study is to understand why the operational life of the master skin is so short (some hour of working) especially when the blade is in contact to the Human skin. Preliminary studies have underlined a recursive crack faults that characterize, the slim extremities of the devices (bar); the first tests, also put in evidence, that the crack location generally lies along an operational deflection mode nodal line.

2. THE OBJECT: SKIN MASTER PLUS

Skin Master Plus is composed of two steel thin plates (inox 304) on which four piezoceramic actuators elements are bonded (1mm thick, PiezoCeramic P841 disk). An extremity sheet (thin slab) is inserted between the two aforesaid slabs and to they berthed by means of braze welding process (Figure 1).

Figure 1: Skin Master Plus device (without handling package)

The sheet is put in vibration from the action of the piezoelectric actuators that opportunely driven, produce vibrations to vhf (around to the 25 KHz) that through the slabs are transmitted to the sheet.

3. SKIN MASTER PLUS FEM MODEL

SKIN MASTER, as previously described, is made of two main elements and an extremity thin plate made of stainless steel 304 and four ceramic piezo elements. The material of the ceramic piezo elements is the P841. Plate elements are used to create the fem model. The ceramic piezo elements have been modeled with plate elements that lie on the skin master holder on both sides (Figure 2). The model is made of 7463 nodes and 6961 CQUAD plate elements. Isotropic material cards are introduced as described in Table 1. Due to the high frequency dynamic problem a finest mesh was created to simulate the blade a of the Skin Master.

	E (N/m2)	ρ (kg/m^3)	ν
Iron	2.E+11	7900	0.33
PiezoCeramic P841	2.E+11	7700	0.34

Table 1: Material Table

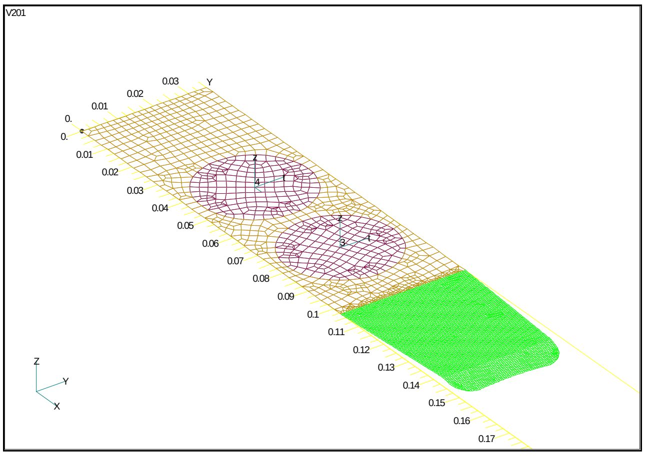

Figure 2: Skin Master FEM Model

4. BOUNDARY CONDITION

During the cosmetic treatment the operator puts in touch the Skin Master blade with the patient face skin. The contact between the skin and the blade involve a change of the blade boundary condition: from free-free condition to pinned one. Is impossible to determinate the read boundary condition in terms of local stiffness because it depends from the operator hand: due to the treatment he can put more pressure on the face and the local stiffness can change also because each patient has a different skin. The extreme boundary condition can be: free-free and fixed one.

Due to these considerations two different runs were performed on the FEM model related with the two different boundary conditions. A third but common boundary condition was also introduced to simulate the operator holder (Figure 3).

It is therefore initially proceeded to the extraction of the natural mode frequencies of the system in order to identify the main characteristics of the system in free-free condition.

Subsequently they have been introduced on four points pinned boundary condition (indicates in Figure 3 with the blue triangles) in order to verify eventual influences on the natural frequencies of the system; it turns out to you, like extension successive, have evidenced a light elevation of the own frequencies for this new tie condition, with inferior values however to 2%.

The real modal analysis Sol 103 solution shows a light high modal density of the system: in the 0-36 *kHz* frequency range 64 eng-values are extracted. In the last 20 *kHz* 22 eigen-values are present.

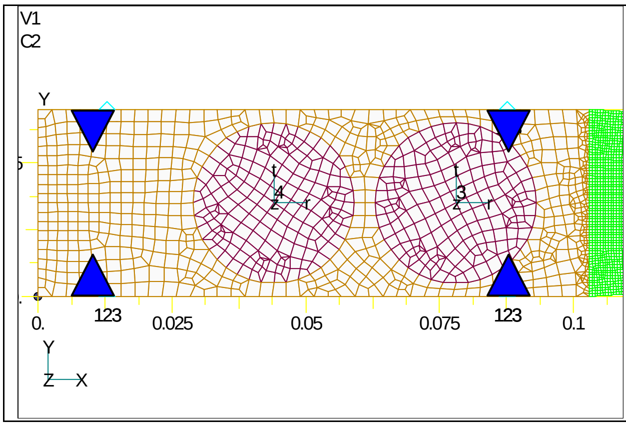

Figure 3: Boundary condition on the operator holder

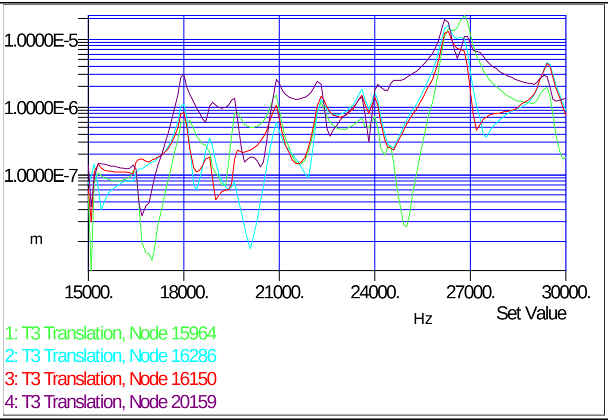

Figure 4: Influence of the boundary condition on the system natural frequencies

Piezo- strain actuation formulation

Using the classic formulation of the "strain actuation" model, the force distribution for each pair of actuators has been introduced , according the formula:

$$F_x = \frac{3}{2}\frac{\psi}{\psi+6}2bE_p d_{31}V = \frac{3}{2}\frac{\psi}{\psi+6}\frac{aE_p}{1-\nu_p}d_{31}V = \frac{3}{2}F_{1D} \quad \text{with } \psi = \frac{E_{pe}t_{pe}}{E_p t_p} \qquad (1)$$

by which, with reference to the physical characteristics of the actuators and the bar and to the characteristics of the electric driving field it is possible to calculate the value of the radial force of excitation.

Under the spectral point of view , the piezo are excited with different type of signal so to excite a typical resonance frequency of the extremities sheet close to 26 *kHz*. With a sinusoidal signal at 26 *kHz* the blade displacement is around 20 mm.

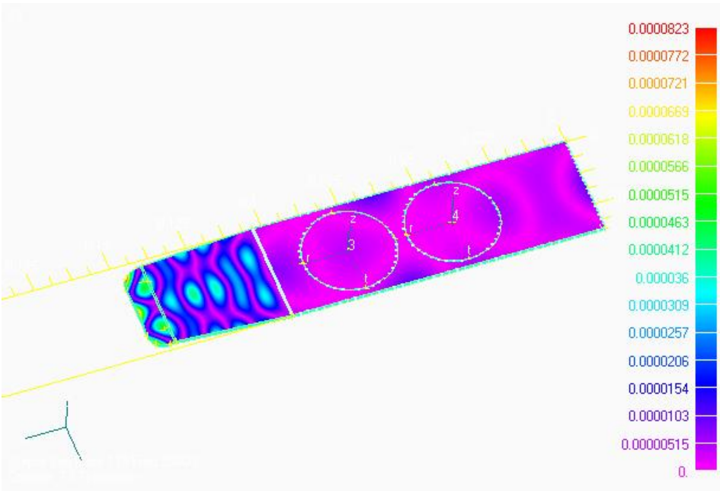

Figure 5: Operative deformation with sinusoidal force signal at 26kHz.

4. SKIN MASTER PLUS EXPERIMENTAL MEASUREMENTS

In order to identify the operative deformed shape and the levels of medium speeds of vibration of the Skin Master extremity's blade, an experimental test campaign has been performed by the use of a scanning laser vibrometer (Polytec PSV 400); the experimental set up is shown in next picture 6 and 7.

Figure 6: PolyTec Laser PSV 400

Figure 7: Skin Master Set Up and acquisition grid

A of 40 x 40 points grid was generated on the blade Skin Master device and an acquisition frequency range up to 32 KHz has been used; the Biorem generator unit has then been ised to drive the system with several signals according to the specific cosmetics treatment. The signals tested on the Skin Master were four: Peeling, Moisturising, Circulation and Clearing. The peeling signal, a burst 26*kHz* sine signal with 100Hz frequency modulation signals, seemed to present the heaviest values in term of displacements and power developed. All the acquisition were made at the 80% and 100% of the maximum power, to simulate the operative possibilities.
A microphone was also introduced in the measurement chain, very close to the plate shoulder, and used as reference signal; this second signal is necessary for the phase reference, in the case in which the operating mode shape are wanted to be extracted.
We remember that the system works essentially excited in resonance (the generator try to identify the piezo resonance frequency and generate a sinusoidal frequency at the same frequency of the structure resonance frequency that usually is around the 26 kHz).
In any case the system generate component in the frequency range 0-30 *kHZ* even if the values in amplitude are smaller than the values at resonance frequency.
Figure 8 shows the mean velocity in rms on the Skin Master blade using different signals with 50% of the maximum power. The system resonance frequency is around 26 kHz but several sinusoidal components are present, in the whole frequency range.

	Experimental (Hz)	FEM (Hz)
Op. Mode Shape n°1	1240	1316.5
Op. Mode Shape n°2	3205	4000.0
Op. Mode Shape n°3	8185	6907.67
Op. Mode Shape n°4	11800	12037
Op. Mode Shape n°5	17000	18063.64
Op. Mode Shape °6	19450	20287
Op. Mode Shape n°7	25590	26194
Op. Mode Shape n°8	28290	28549

Table 2: Operative mode Shape

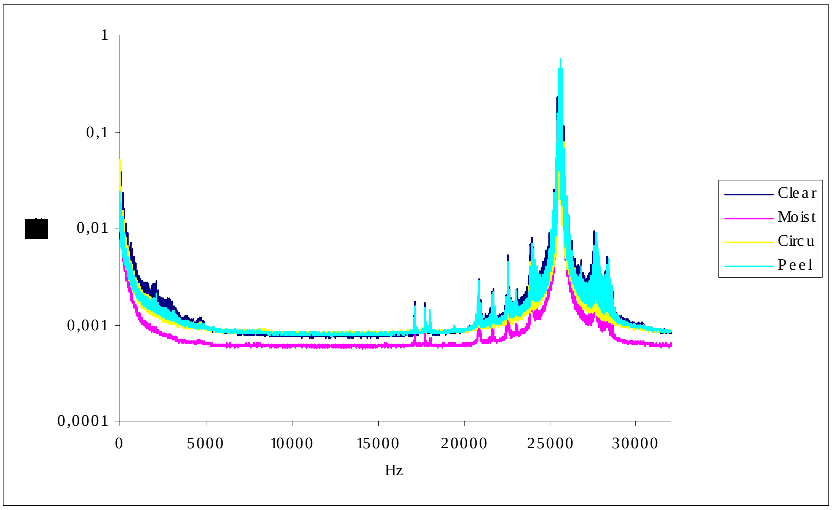

Figure 8: Response of the system using several excitation signals

Table 2 shows the experimental eigen-frequency extracted from the Laser vibrometer acquisition and the result of the FEM real eig-values analysis. A good accordance between the two model are found.
Figure 10 show the experimental operative mode shape and the Fem extract at 6907 Hz.

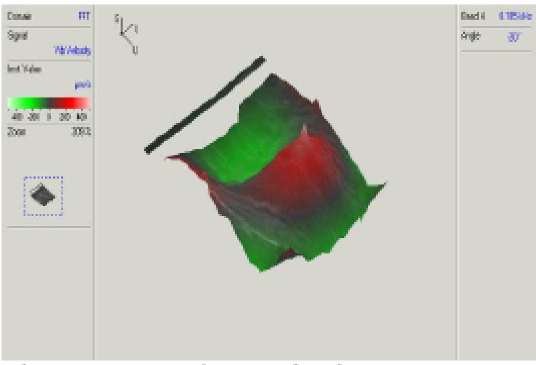

Figure 9: Operative Mode Shape at 6185 *Hz*

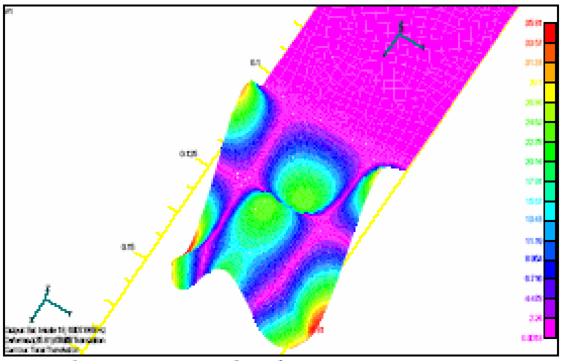

Figure 10: Mode Shape at 6907.67 Hz

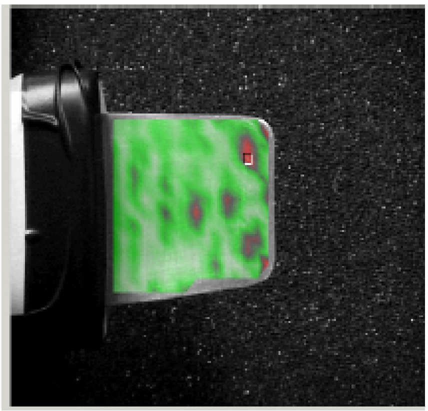

Figure 11: Displacement 25.88k*Hz*

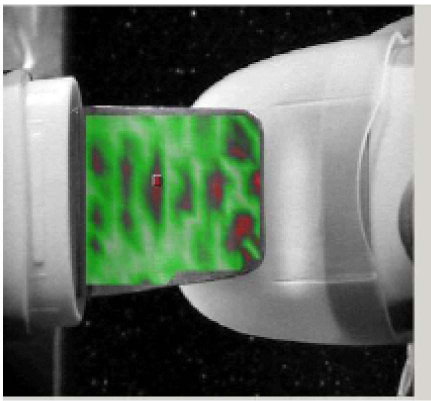

Figure 12: Displacement 25.88k*Hz*

It was also investigated the effect of the boundary condition, repeating the measurements in "free" condition as well (figure 11 and 12).

6. FATIGUE ANALYSIS

Based on the experimental and numerical results a Fem Fatigue model was implemented based on the previous implemented Fem model. The Boundary conditions introduced in the FEM model are: four support as showed in the Figure 3 and the extreme part of the blade is simple supported.

6.1 Iron S-N fatigue curve

In materials science, fatigue is the progressive, localised, and permanent structural damage that occurs when a material is subjected to cyclic or fluctuating strains at nominal stresses that have maximum values less than (often much less than) the static yield strength of the material. The resulting stress is thus well below the ultimate tensile stress, or even the yield stress of the material, yet still cause catastrophic failure. Fatigue should not be confused with cyclic overload, such as the bending of a paperclip. A metal paperclip can be bent past its yield point (i.e., bent so it will stay bent) without breaking, but repeated bending in the same section of wire will cause the material to fail. In high-cycle fatigue situations, materials performance is commonly characterised by an S-N curve, also known as a Wöhler curve. S-N curves are derived from tests on samples of the material to be characterised (often called coupons) where a regular sinusoidal stress is applied by a testing machine which also counts the number of cycles to failure. This process is sometimes known as coupon testing. Each coupon test generates a point on the plot though in some cases there is a runout where the time to failure exceeds that available for the test (see censoring). Analysis of fatigue data requires techniques from statistics, especially survival analysis and linear regression.[3] Figure 13 shows typical SN curve for different type of Steel. The steel is characterized by an asymptotic behaviour when the cycles exceed the 106 values. The Skin master works at 26k Hz that means a number of 9.36*107 in one hour. To increase the life time of the blade the stress developed during the working should be in the low part of the S-N graft. The Skin Master is made by ANSI 4330 /Steel 340 that have low performance in term of fatigue life compared to other steel like En 25 e En25 Dura.

6.2 FEM Fatigue results

To determine the fatigue life of skin master using Fem Tools two input are important: the S-N curve of the material and the boundary condition of the skin master blade. As previously describe the contact condition between the human skin and the blade are determined by the operator hand pressure and the type of skin of the patient: condition that are difficult to determine. In this condition a probabilistic study was performed changing the contact skin blade condition introducing springs elements with different stiffness values. This analysis shows that increasing the stiffness the fatigue life decrease. So the extreme life time are the free-free boundary conditions and pinned one. Figure 14 shows typical final results of the fatigue analysis. Zone characterized by red colors indicate parts of the blade with higher possibilities to go in failures. These results agree with the failures noticed during the normal use of the Skin Master. The Fem numerical results give values of the stress between 57e3 lbf/in2 and 63e3 lbf/in2 according to the free-free or pinned boundary condition. Introducing theses values in the S-N ANSI 4330 curve gives a life time of 10e7 cycles. Introducing a scattering factor of 2 the life time goes down to 10e5 cycles that means few minutes of life. If a different type of steel is used, like 25 Dura, the life time will increase to values of cycle of 10e7 that means infinite life time.

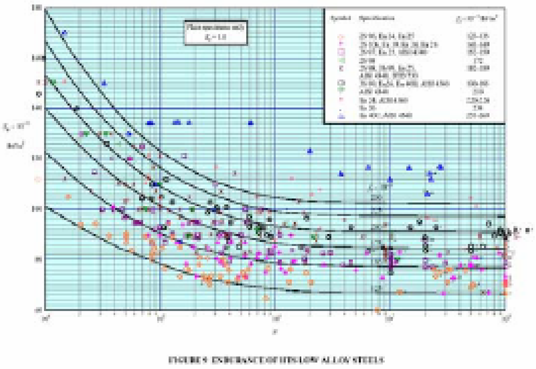

Figure 13: SN Curves for Steel

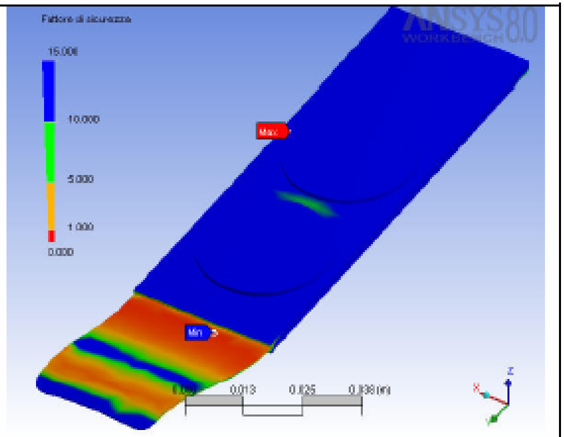

Figure 14: Security Fatigue Factor

7.CONCLUSION

The results have shown a good accordance of the numerical model with the results derived from the experimental campaign, giving enough guarantee that the forecasts related to the lifetime prediction developed on the base of the aforesaid model can sufficiently been considered accurate.

From the analysis of the results it results evident a non optimal behaviour of the material used for the bar, in terms of resistance to work; such a circumstance justifies the reason of the system breakups in correspondence of a brief operational life.

Such behaviour seems to be able to be resolved using steels with improved characteristics ; the use of some of them (with values of greater ft of 150 lbf/in2s) hands in fact to an endless life of the Bar.

8. REFERENCES

[1] A.W. Leissa, Vibration of shells, American Institute of Physics, Woodbury, New York, 1993.
[2] Skin Master Plus technical sheet
[3] W. Schutz (1996). A history of fatigue. Engineering Fracture Mechanics 54: 263-300.