FINITE ELEMENT ANALYSIS OF ACTIVITY-DIPS IN NLC-CUT QUARTZ TEMPERATURE SENSORS

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ABSTRACT

The present paper proposes a systematic modal analysis performed with finite element program about thermo-sensitive resonators in NLC cut of quartz (Ref. 1) over a large temperature range. The analysed design consists of small diameter flat parallel, mass-loaded resonators operating on fundamental overtone near 29.2 MHz. We present a description of the influence of several factors on the stability of the mode pattern along temperature variations down to low temperatures. These factors include : thickness of electrodes deposit, diameter of electrodes together with orientation of electrode tabs.

1. INTRODUCTION

Some papers (see Refs. 1,3) have already been devoted to the use of Finite Element Analysis (FEA) for the understanding of activity-dip phenomenon in quartz resonators. The efficiency of FEA in this field mainly depends on the accuracy of material constants and on the possibility to simultaneously fit the actual mode shapes of the mode of interest and the involved spurious modes with a single set of generic interpolating functions while keeping the size of matrix problem as reasonable as possible. The purpose of here-presented study was not to track with the best possible accuracy the activity-dips expected in a given and stable design of thermo-sensitive quartz resonator (TSQR), but to give suggestions for possible optimisation of a new design, characterised by rather small dimensions (cf. Fig. 1) and operating in fundamental thickness mode in so-called NLC orientation (cf. Ref 2). For this singly rotated cut of quartz (ϕ=0, θ=-31.5°), a electric field along the thickness of plate drives only the B-modes, which have then a pure u_1 polarisation, as have C-modes in AT cuts. From the point of view of finite element analysis (FEA) operation on fundamental mode is expectedly easier to model than operation on higher overtone since only one layer of elements with cubic interpolations along the thickness might be sufficient to accurately model the mode pattern, thereby leaving the possibility to perform a rather dense mesh along in-plane axes of the plate.

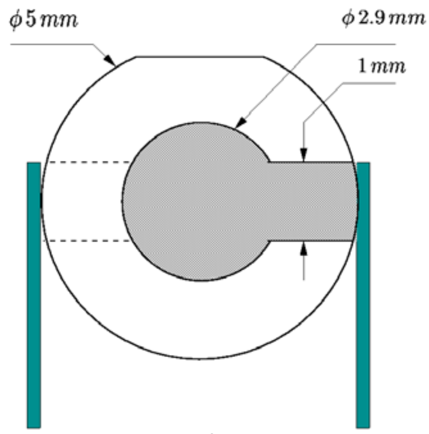

Fig. 1 Design of NLC-cut TSQR

Here-presented work was performed with prismatic finite elements with parallelepipedic shape. For such elements, interpolations are cubic along all directions, with incomplete interpolating functions base along in-plane axes and complete one along the thickness.
The mesh of resonator is presented on Fig. 2. It contains around 4000 nodes arranged into 420 elements : 228 membrane elements (12 nodes) for the modelling of silver electrodes, and 192 tridimensional elements (48 nodes) for the quartz crystal.

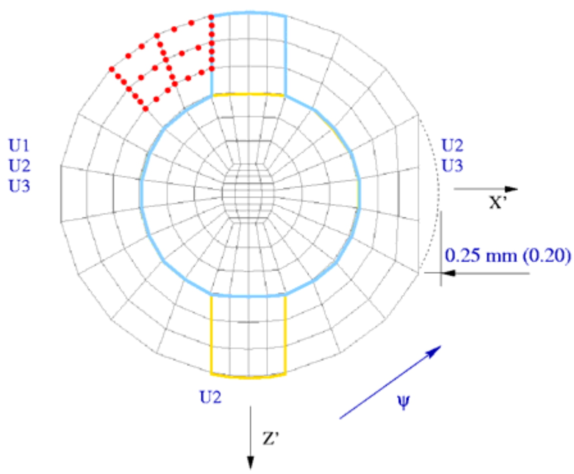

Fig. 2 Actual mesh of TSQR with 48-nodes elements

With a 550 MHz, rather standard personal computer equipped with 1 giga-byte of memory, analysing this structure requires typically between four and six hours of computation to get thirty modes at a given temperature point.

2. MODE SHAPE AND SPECTRUM

Our first work consisted in checking the trapping of the mode shape by the mass loading of electrodes deposit. The following values of thickness were tested for silver plating : 58, 80, 100, 120, 140, 160 nm. The theoretical thickness of the quartz plate itself was initially set to 82 µm for the computations and the electrodes tabs were not taken into account at the beginning of this study. Only fundamental B-mode with associated anharmonic responses were modelled. Experimental checking was possible on a few TSQRs made at AE Lab with only 58nm and 180nm plating. In particular, the spectra of two samples were analysed on our X-ray topography system. Obtained mode patterns are produced in the companion paper, Ref. 4. The frequency range of FEA-predicted spectrum was in general found significantly more restricted than the range predicted by Tiersten and Stevens analytical model. This was confirmed by experiment. Corresponding data are presented on Table 1. We use the common notations (*n,m,p*) for mode identification of the mode pattern, where *n* indicates the overtone number, *m* the number of nodal planes along X-axis, and *p* the number of nodal planes along Z' axis. In all cases, FEA results were searched in frequency windows containing 30 eigenmodes. Corresponding columns are not completely filled in here-produced results, and we even did not try to complete them, according to the following discussion:

- We found many abnormalities of the predicted patterns in runs of program performed with rather thick electrode plating. For instance, an additional mode, (1,1,1)-like, is predicted by FEA in case of 180 *nm* plating. This observation is even reinforced when lowering the plating thickness down to 160 *nm*. In the case of simulations performed for 100 *nm* plating, we obtained two slightly perturbed (1,0,0) patterns at 25°C, separated by only 374 Hz. Predicted patterns for u1 component are presented on Fig. 3. while Fig. 4 presents the predicted patterns for u3. The predicted patterns for u2 are quite identical to the ones for u3, with relatively comparable amplitude. At different temperatures, for instance 40°C or 10°C, the simulation predicts only one (1,0,0) mode, with a very smooth shape. This is just how FEA predicts activity-dips. In the considered case, examining the patterns of Fig 4 shows that the main component u1 is coupled with combined face shear and flexure wave travelling along Z' direction.

- From another hand, X-Rays topographs presented in Figs 14-17 of the companion paper for the thicker plating show a strong offcentering and a π/4 rotation of the mode shape which could not be explained by introducing a defect of parallelism of the quartz plate in finite element analysis, for instance. At the same time, introducing such defect in simulations for 58 *nm* plating improved the realism of simulations, as can be observed when comparing Fig. 5 of the present paper (defect 0.5% between centre and the circumference of plate in X-direction) with Figs. 8-11 of Ref. 4. Distortion of topographs obtained for (110) and (102) modes (Figs. 5-6 of Ref. 4) are left over from such comparison because of the actually high level of drive used during X-ray analysis : in case of resonant modes with very close frequencies, the actual response does not come from a single eigenmode.

Combining our feeling of better understanding of the behaviour of the 58 *nm*-plated sample and the prediction of many activity dips for designs with thicker plating , we decided to pursue the systematic analysis of the influence of construction parameters with a thickness of plating fixed to 58 *nm*. For this case, the second FEA column in Table I was obtained when taking into accounts electrode tabs in the FEA model. It is worth remarking that this change was sufficient to modify the ordering of the close modes labelled (110) and (102) making it conform to the measured order. This confirms the importance of electrode tabs previously asserted at Ref. 3.

Plating 180 *nm*			
	$f - f_{100}$ (kHz)		
mode	Tiersten	FEA	Measured
1,0,1	44	24	39
1,0,2	134	59	61
1,1,0	144	61	-
1,1,1	189	97	
1,0,3	267	107	154
1,1,2	278		
1,1,3	411		
1,2,0	421		
1,0,4	440		
1,2,1	466		

Plating 58 *nm*				
	$f - f_{100}$ (kHz)			
mode	Tiersten	FEA		Measured
1,0,1	42	23	22	21
1,0,2	123	55	53.7	46
1,1,0	125	54	54	52
1,1,1	-	87	87	79
1,0,3	-	98	94	92
1,1,2	-	128		119
1,2,0	-	137		125
1,0,4	-	150		138
1,2,1	-			168

Table 1 - Frequency spectrum from models and exp.

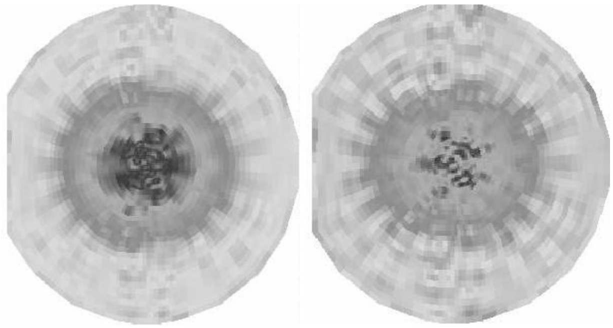

Fig.3 u1 patterns of twin modes (100nm plating)

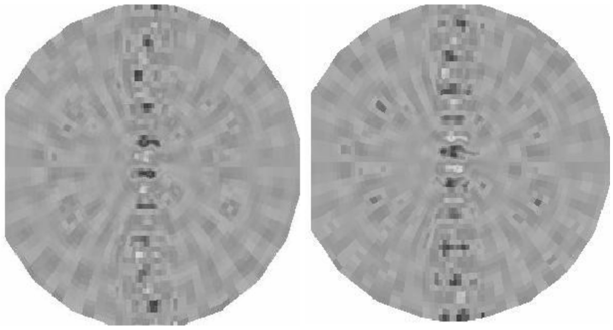

Fig.4 u3 patterns of twin modes (100nm plating)

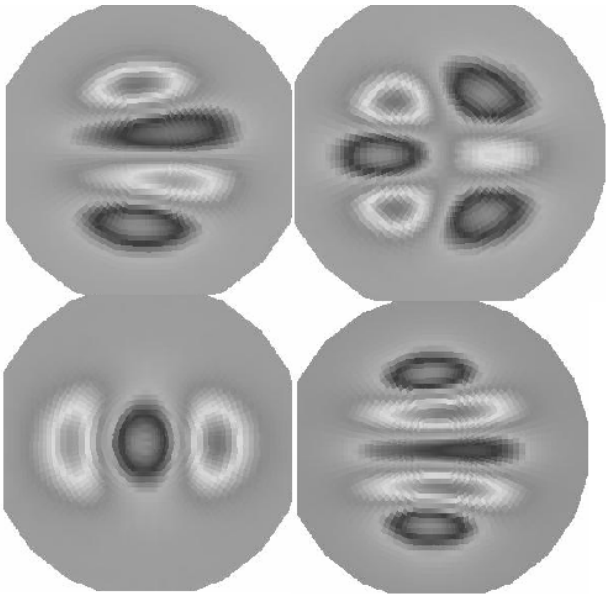

Fig. 5 u1 patterns with defect of parallelism

3. TABS AND FLAT ORIENTATION

To more precisely investigate the influence of tabs, we simulated by FEA the frequency temperature characteristics of TSQR by 10°C increment between 20°C and 100°C. This was intended for the design with electrode tabs and silver plating 58 *nm* thick, upon rotating the material constants around the plate normal by the following angles : $\psi=0$, $\pi/8$, $\pi/4$, $3\pi/8$, $\pi/2$, $5\pi/8$, $3\pi/4$, $7\pi/8$. Only the values of ψ in the range [0- $\pi/2$] have been checked yet. Nevertheless, it was found that rotating the whole shape of resonator has definite impact on the occurrence of activity-dips. For instance, with $\psi=0$, the simulation predicted a splitting of (1,0,0) mode at 40°C. With $\psi=\pi/8$, the same kind of splitting occurred at 60°C, and, with $\psi=\pi/4$, such incident was predicted at 70°C. At first sight, these cases seem to concern the *same* activity-dip, continuously affected by the rotation of the design around its own normal. We intend to confirm this by a more refined analysis with smaller steps for ψ and for the temperature. We have previously proposed at Ref. 2 a method to quantitatively appreciate the strength of the dip : it consists of plotting the deviation between the actual frequency-temperature characteristic and a cubic fit of it. When the mode of interest splits in two twin modes under the action of thermo-dependent coupling, the frequencies of the twins are symmetrically located below and above the frequency predicted by the least cubic fit. We present such a typical situation on Fig. 6, for the case of the predicted dip at 40°C and $\psi=0$, which yields two (1,0,0)–like mode patterns represented on Fig. 7, separated by only 330 Hz.

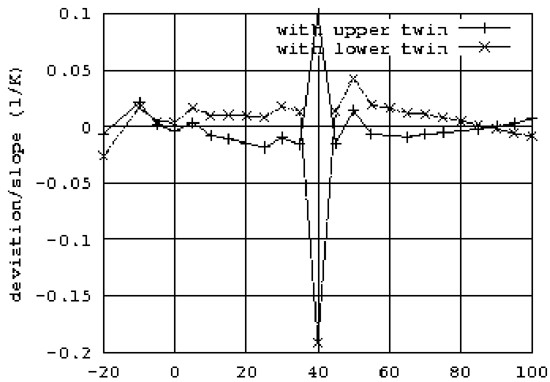

Fig. 6 use of standard deviation to track activity-dip

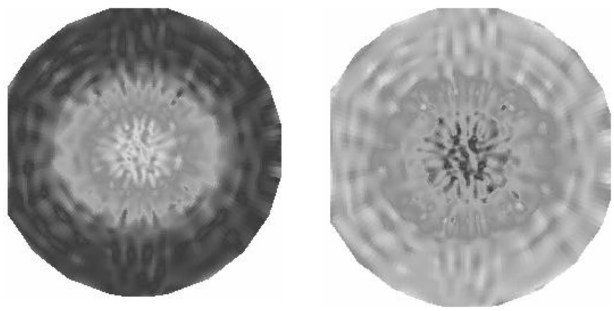

Fig. 7 twinning of mode patterns (u1) at 40°C

Farther, a perturbation of (1,0,0) mode was predicted only at 100°C with $\psi=3\pi/4$, but this perturbation was very slight, and, at the end, only the +40°C point corresponded to very slight defect of smoothness of the mode pattern with $\psi=\pi/2$. It was not possible to relate those temperature-dependent perturbations with already investigated ones, due to the noisy character of simulations for *u2* and *u3* minor components of the mode. It must be recalled that the proper identification of activity dip caused by high order harmonics of flexure or face shear waves may imply the use of a specific finite element mesh, depending on the number of oscillations of the spurious mode concerned. Other clues of activity-dips were found acting on anharmonic modes such (1,0,1) and (1,0,2), (1,0,3) for various parameters.

4. ELECTRODE DIAMETER AND FLAT

On previous results of simulations, the distance between the flat and the circumference of the was set equal to 0.25 *mm*. After setting it equal to 0.20 mm we got a clear perturbation of (1,0,0) mode at 60°C on the frequency-temperature characteristic by 10°C steps. Interestingly enough, at 70°C the (1,0,0) mode pattern became smooth, while the (1,0,1) became perturbed. The patterns obtained for the minor components of the vibration are still too noisy to estimate if both perturbations come from the same kind of spurious mode. If it is true, this spurious mode would be not so temperature–sensitive and crossed by the successive thickness modes which all exhibit temperature sensitivities near –1000Hz/ for this design. At this moment, the steps used for parameters changes are still a bit large to allow for such a continuous tracking of the activity dips. Nevertheless, it is common situation to observe that a neighbouring anharmonic mode becomes perturbed instead a previous one after a change of parameter. For the class of here-studied resonator, we estimate that temperature steps of 2.5°C may be sufficient to accurately follow the continuous evolution of activity dips along most of geometrical parameters changes considered here.

We performed also other simulations, still for the case of 58 nm plating and with electrode tabs, together with flat-to-circumference distance set equal to 0.25 *mm*, but with electrodes diameters decreased to 2.4, 2.0 and 1.6 *mm*. Temperature-dependent perturbations were still predicted, but could not be connected with previously investigated ones. By the way, diminishing electrode diameter by 0.5 or 0.4 *mm* is a big change, as can be checked on Fig. 8, showing the mode pattern at 40°C for the main mode and electrode diameter equal to 2.0 mm. The effect of tabs is comparatively reinforced by the reduction of electrode diameter, so that the vibration is much less trapped along the tab orientation (vertical on the picture). This involves some change of the spectrum and mode shape of higher anharmonic modes, making the analysis difficult to compare with previously presented ones.

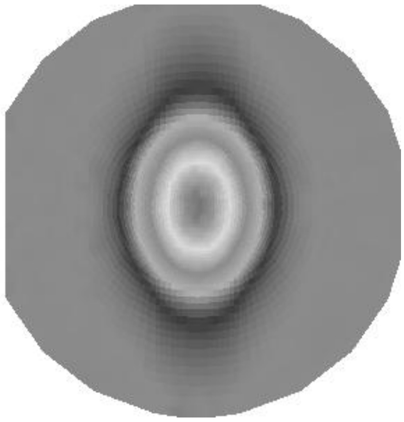

Fig. 8 : (100) mode pattern for ϕ electrodes 2.0mm.

5. CONCLUSION

Although the lack of computation of admittance still kept the FEA interpretation of the stability of mode patterns *vs* temperature on a somewhat qualitative base, it persistently confirmed the important role played by the electrode tabs in the behaviour of TSQR along temperature variations. Also, it was found that geometrical defects such as parallelism impact on the occurrence of activity dips.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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