7 TH EUROPEAN FREQUENCY AND TIME FORUM NEUCHÂTEL - 16 - 17 - 18 MARCH 1993

Session Number

DEVELOPMENT OF QUARTZ-RESONANT-SENSORS USING FEM

Christian Reichinger

TU München, Lehrstuhl für Elektrische Meßtechnik

ABSTRACT

The design of vibrating quartz sensors for force or pressure is a problem that can only be solved by computer simulation. One possibility is the use of finite element analysis.
The FEM program must be able to compute the piezoelectric coupling between the electric stimulation and the mechanical vibration of three-dimensional anisotropic bodies as well as the damping influence of the mechanical clamping. The determination of the force vs. frequency characteristic requires the implementation of the acoustoelastic effect which describes the change of the elastic wave velocity as a function of mechanical stress. Based on the standard FEM program ANSYS the necessary expansion was made. The simulation results of a typical quartz sensor are presentated.

Quartz resonant sensors, finite element analysis, piezoelectric simulation, acoustoelastic effect

1. INTRODUCTION

Quartz crystals as sensors for physical quantities that change the resonant frequency of the crystal directly have a high accuracy due to the high quality of the resonating quartz.

With the development of force or pressure sensors of this type the mounting must impact the load or pressure to the quartz resonator. A stable, loadable mounting will tend to stop any vibration in the quartz by damping. New quartz resonator geometries with a high quality in spite of the damping caused by the mounting are necessary to avoid this problem.

This design problem can be solved by using the finite element method (FEM). A new method of simulating the damping influence of the quartz mounting is introduced. Furthermore, the integration of higher order elastic coefficients in a finite element is described. The consideration of these higher order terms leads to a FE model that can calculate the change of the resonant frequency due to mechanical loads such as forces or pressures in a mounted quartz of arbitrary geometry in an arbitrary mounting.

For validation purposes the computed results with a quartz double-ended tuning fork are compared with measured values.

2. SIMULATION OF QUARTZ RESONATORS WITH ANSYS

The element library of ANSYS offers a three-dimensional multi-field solid which can calculate the piezoelectric effect. This effect describes the coupling between mechanical strain and electric fields in anisotropic materials. For the simulation the resonator geometry must be assembled with finite elements of this type. As the values of the elastic stiffness tensor, the piezoelectric tensor, the dielectric tensor and the mass density of quartz are known all undamped mechanical resonant frequencies possible in the quartz simulation model can be calculated. The resonant frequencies that can be stimulated piezoelectrically are determined by two calculations with different boundary conditions (i.e. open and shorted electrodes).

For the calculation of damped quartz resonators all possible parameters influencing the quartz must be considered. These parameters are the internal damping of the quartz material, the damping of the electrode material, the damping caused by the surrounding medium and the damping of the mechanical clamping. The first three damping influences can be considered when the material constants, especially the damping values, are known for the used materials. However, in most cases the damping influence of the mechanical clamping is much greater than the influence of the three others is. Because of that the implementation of the damping of the mechanical clamping is most important to get good results of the complete quartz damping.

With calculations including the above described damping effects the impedance of the quartz model as a function of the frequency is determined. From the impedance curve the four parameters C0, C1, L1 and R1 of the electric equivalent circuit diagram of a damped quartz resonator are found.

3. CLAMPING ELEMENT FOR QUARTZ RESONATORS

As the power losses of quartz resonators are mostly caused by mechanical clamping suitable models for the clamping must be developed.

One possibility is to model all parts of the clamping exactly. This leads to a very complex simulation model which is not necessarily more accurate with regard to the energy consumption. There is still the difficulty of defining all material parameters of the clamping, especially those which describe the damping.

Because of that a new clamping element is introduced which is as simple as possible. It must be attached at the quartz surfaces which are in contact with the mechanical clamping. The equation of the clamping element is a function of the contact area and only one other variable D. The basis of the equation is a mathematic consideration. This is the reason why the clamping element is absolutly independent of the clamping material. The damping of the clamping element as a function of D has a special characteristic, as can be seen in figure 1. The maximum damping of the clamping element at $D = D^*$ describes the worst case of damping. No mechanical clamping at the modelled surface can have a greater damping. This means that the simulated value of the resonant resistance R1 of the quartz electrical equivalent circuit diagramm as a measure of the complete damping is always greater than the measured value when the maximum damping of the clamping element is used in the simulation ($D = D^*$).

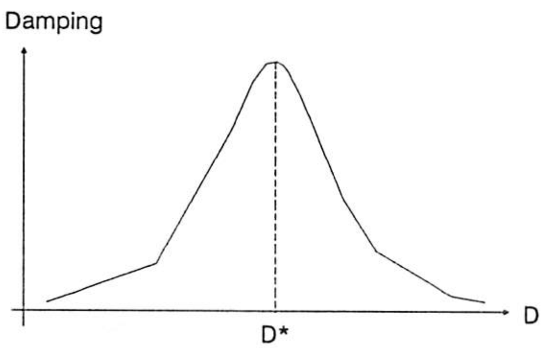

Fig. 1: Damping characteristic of the clamping element

On the other hand the simulation result depends on the exactness of the simulation model, too. To determine the exactness of a simulation model an error estimator for dynamic problems is used. This error estimator is similar to that given for static problems (Ref. 1). It weights the deviations of the simulated mechanical stress from a continuous stress profile. The deviation of the node stresses from the mean stress of a finite element in connection with the node displacements is used to compute the error energy. A common criterion for a good FE model is an error energy evenly distributed over all elements. With a very good simulation model the ratio E of the maximum error energy to the minimum error energy is nearly 1.

As it is normally impossible to create a simulation model with a value of $E = 1$ another way of determining the exact value of R1 must be found. The solution is to build two ore more simulation models with different values of

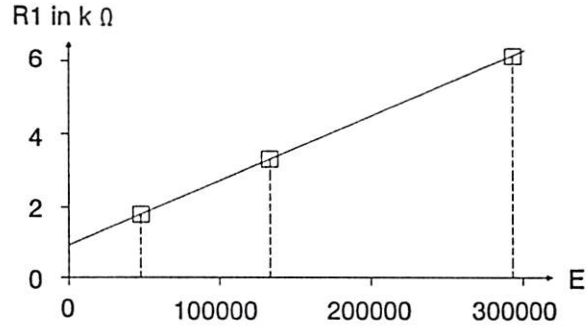

Fig. 2: Extrapolation of the resonant resistance R1

E. Then each model has another worst case value for R1. In figure 2 the E and the corresponding R1 values of three simulations are fitted by a function. The extrapolation of this fitted curve leads to the most exact value of R1 at $E = 1$. It must be remarked that the fitted curve is not always a straight line as in figure 2. There are curves of higher order depending on the complexity of the quartz resonator, too.

But by means of this new clamping element real quartz resonantors can be calculated with a high accuracy.

4. COMPUTATION OF THE ACOUSTOELASTIC EFFECT

Until now the equations of the simulation program were linear. They describe the stress-strain and the strain-displacement characteristic. In reality these equations are nonlinear.

The acoustoelastic effect is determined by the nonlinearities of these characteristics. Because of that two nonlinearities are added to the simulation program, first the material nonlinearity and second the geometric nonlinearity.

Material nonlinearity is called the fact that the elastic stiffness tensor which describes the linear characteristic between stress and strain is not independent from the stress but changes with the stress. The amount of the changing can be computed using the elastic constants of third order (Ref. 2).

Geometric nonlinearities must be considered when there are displacements which are not small compared to the resonator geometry. In this case the linear characteristic between strain and displacement is no more sufficient for good simulation results. The formulae that take into consideration the geometric nonlinearities can be found in Ref. 3.

The FE program ANSYS allows only the computation with geometric nonlinearities. For the consideration of the material nonlinearities another program was developed. Both nonlinearities change in a first simulation step the stiffness matrix of the simulation model. In a second simulation step the change of the resonant frequency due to the acting forces or pressures is determined by means of the updated stiffness matrix.

Beside this two nonlinearities there are two other quantities that can change the resonant frequency of a quartz resonator due to the acoustoelastic effect: the change of the mass density and the change of the geometric dimensions of the resonator. With the quartz resonators of our interest these two additional effects are of minor importance as the simulation results prove in the following chapter.

5. SIMULATION RESULTS AND MEASURED VALUES

A typical example for a quartz resonant force sensor is a double-ended tuning fork. A resonator of this type is deliverable from Micro Crystal in Grenchen, Switzerland. Figure 3 shows such a sensor quartz. For the simulation of a quarter of the resonator a FE model with 240 nodes and 123 elements is used. The measured values are derived from a clamped resonator but the sensitivity value is taken from a data sheet.

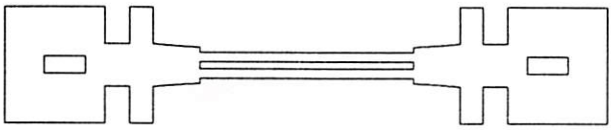

Fig. 3: Quartz double-ended tuning fork

The following table shows a comparison between measured and computed values.

Quantity	measured value	simulated value
fs	47194 Hz	49855 Hz
C0	5.4 pF	1.9 pF
C1	38 fF	8.1 fF
L1	300 H	1255 H
R1	17.5 kohms	24.983 kohms

The simulated resonant frequency fs is 5.6 % to high. This inaccuracy can be reduced by using finer FE meshes (more nodes and elements) but this would increase the calculating time drastically.
The measured value of C0 is higher than the calculated value because there are additional stray capacitances of the wires and the housing.
The deviation of the two quantities fs and C0 affects the values of C1 and L1. Improvements of the simulation with regard to fs and C0 automatically result in better values with C1 and L1.

The results commented above are nearly independent from the damping of the mechanical clamping and can be computed using the standard features of ANSYS. They do not vary by much when the clamping element is omitted. But the calculation of the resonant resistance R1 needs the new clamping element.

The simulation result of R1 is not the most exact value. The value of E is 604 with this simulation model and there are not enough other simulation models of the same resonator with other values of E. So the extrapolation to the value E = 1 is not possible yet. Another interesting thing is the composition of the R1 value. The portion of the quartz damping is 2 ohms, the portion of the air damping 408 ohms. The damping of the electrode material is not included. This means that 98 % of the resonant resistance R1 of the tuning fork are caused by the mechanical clamping when using this not optimal simulation model.

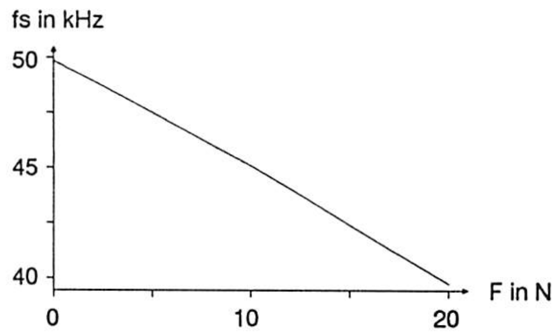

Fig. 4: Force vs. frequency characteristic

The most important quantity of a sensor is the sensitivity. The calculation of the force sensitivity of the tuning fork is made possible by the material and geometric nonlinearities. Figure 4 shows the force vs. frequency characteristic of the tuning fork loaded with a compressive force F. The relative sensitivity determined by simulation is -1.01 % / N. The data sheet of the quartz sensor has a value of -1 % / N. The good agreement of simulated an 'measured' value shows that the change of the mass density and the resonator geometry due to the compressive force F has no important influence on the change of the resonant frequency.

6. CONCLUSION

The expansion of the standard FEM program ANSYS with a new clamping element in connection with an error estimator for dynamic problems makes the simulation of real quartz resonators of arbitrary geometry in an arbitrary mounting possible. The additional consideration of material and geometric nonlinearities leads to a simulation program by means of that the design of quartz-resonant-sensors for force or pressure is possible. The development of the sensor mounting and housing is another task that can be solved with ANSYS, too.

7. REFERENCES

[1] Zienkiewicz, O. C.; Zhu, J. Z.: A simple error estimator and adaptive procedure for practical engineering analysis. - in: International Journal for Numerical Methods in Engineering, Vol. 24, pp 337-357, 1987

[2] Nalamwar, A. L.; Epstein, M.: Surface acoustic waves in strained media. - in: Journal of Applied Physics, Vol. 47, No. 1, pp 43-48, 1976

[3] Zienkiewicz, O. C.: Methode der finiten Elemente. - Hanser Verlag, München, 1975