Measurement of Spurious Resonances of Crystal Units Using Network Analysers with Error Correction

Bernd W. Neubig
TELE QUARZ GROUP
D-74924 Neckarbischofsheim
Germany

Abstract

1. Introduction

The hybrid bridge technique for the measurement of spurios responses as standardized by IEC 283 (1968) [3] has significant limitations in accuracy and reproducibility. Significant progress has been made in the last years applying modern network analysers in connection with error correction methods to the measurement of crystal units [6].

The paper presents a systematic approach to adapt the new techniques to the measurement of spurious responses. The goal is to use the standard test set-up (such as the π-network or a s-parameter test fixture) as it is used for the determination of the crystal parameters of the main mode [5]. In connection with the published method for the measuerement of load resonance parameters[7], all crystal parameters can then be measured with one unique set-up configuration.

2. Classification of spurious responses

Unwanted or spurious modes have different origin and appearance. They can be

(1) anharmonic resonances of the same vibration mode (usually shear mode), whose frequency is in general above the relevant main mode (see Fig.1 [8]). These resonances are determined by the equation

$$f_{mnp} = \frac{1}{2}\sqrt{\frac{1}{\rho}}\sqrt{\frac{c_{65}\,n^2}{t^2} + \frac{c_{11}\,m^2}{l_x^2} + \frac{c_{56}\,p^2}{l_y^2}}$$

(2) unwanted modes (and overtones thereof) of other vibration modes, which may lie below or above the desired mode.

Resonant Vibrations of a Quartz Plate

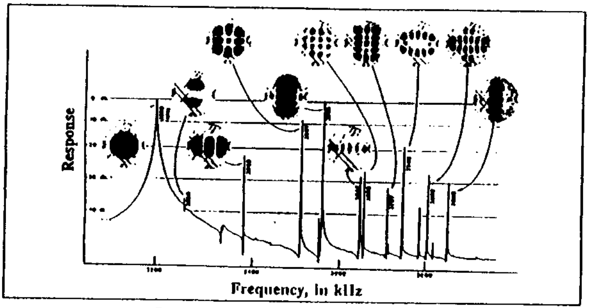


Fig. 1 X-ray topographs (2Ī·0 plane) of various modes excited during a frequency scan of a fundamental mode, circular, AT-cut resonator. The first peak, at 3.2 MHz, is the main mode; all others are unwanted modes. Dark areas correspond to high amplitudes of displacement.

Spurious modes can be

(i) isolated from the main mode, or can be

(ii) mechanically coupled to it, causing non-linear effects which depend on drive level (power dissipation) etc.

Spurious modes can lie

(I) very close to the main mode (a few kHz), such that the peak of the spur is on the slope of the main response.

(II) well apart from the main mode, and therefore can be considered as a separate peak.

Unwanted modes can cause problems

(a) in filters by distortion of the transfer characteristic in the pass band or the stop band: attenuation "dips" and phase discontiuities in the pass band, detoriation of the attenuation in the stop band

(b) in oscillators, the working frequency can "jump" to a strong unwanted mode or the frequency response can show discontinuities ("activity dips") at particular operation conditions (temperature, load capacitance/pulling voltage, drive level). VCXOs can show "dips" ins the pulling characteristic (frequency vs. pulling voltage) or in the response of the deviation vs. modulation frequency. TCXOs can show "dips" in the frequency vs. temperature characteristics.

In the following we will distinguish phenomenologically four different cases:

case A: strong spurs well "isolated" from the main mode,
case B: weak spurs well "isolated" from the main mode,
case C: strong spurs in the vicinity of the main modes,
case D: weak spurs in the vicinity of the main mode.

These cases are depicted in Fig.2.

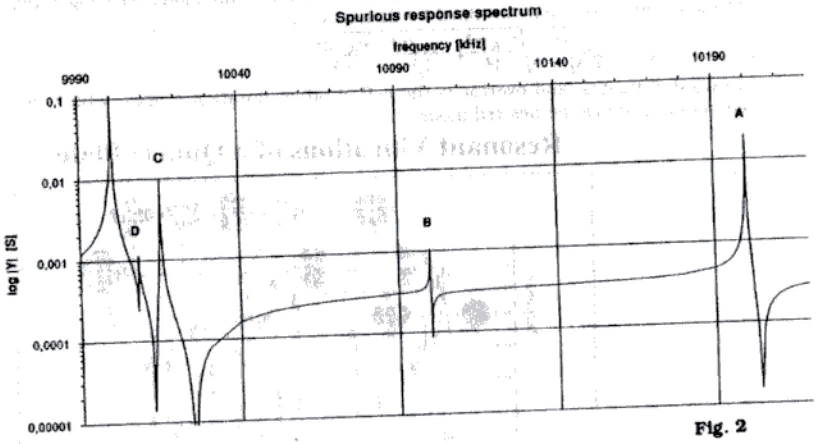


Fig. 2

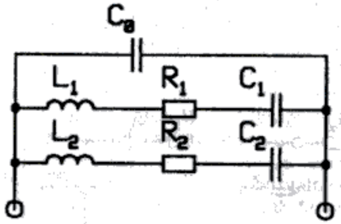
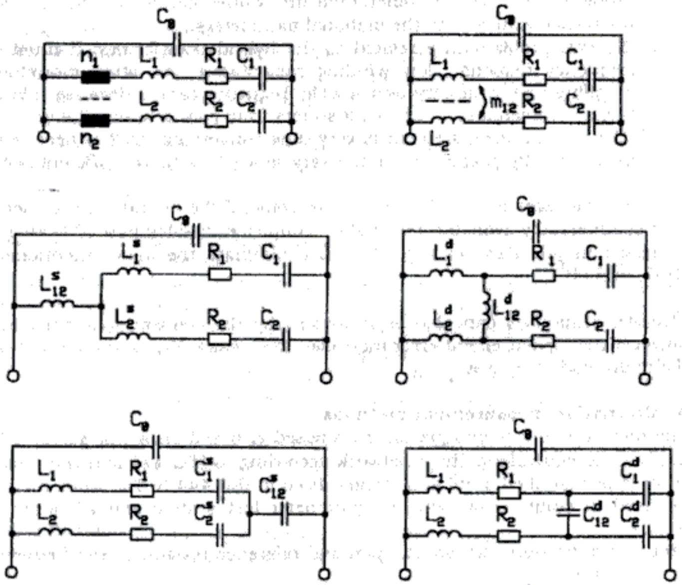


Fig. 3

3. Equivalent electrical circuits

Non-coupled resonances can be represented by seperate series resonance circuits all connected in parallel to the static capacitance C_0. In the following we use the symbols C_0 for static capacitance, L_1,C_1,R_1 for the motional parameters of the first (main) mode, and L_i, C_i, R_i with $i = 2, 3, 4,...$ for the i-th (spurious) mode (see Fig.3). Resonances, which are mechanically coupled, must be represented electrically by a coupling circuit such as a transformer or an equivalent coupler e.g. three capacitors or inductors in delta- or star configuration, where one or two of them may have negative element values. Possible circuits are summarized in Fig.4.

Fig. 4

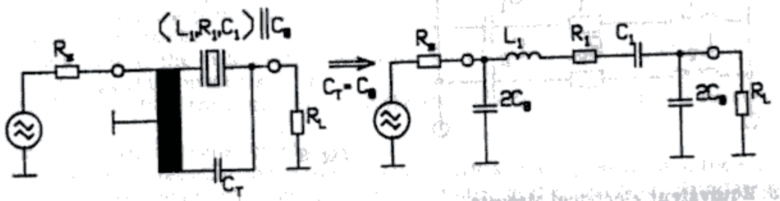


4. Classical measurement methods

The classical measurement technique for spurious modes is the hybrid-coil method, described by Horton and Smythe [1] and Priebe [2], which was standardized in IEC 283 [3].

It uses a differential transformer with a variable capacitor C_C in the second branch to "compensate" the static capacitance C_0 (see Fig.5).

Fig. 5



Due to its simplicity in practical application (once, the hybrid transformer is made ...), this method is very popular. However it has significant disadvantages:

(1) Even if C_0 is compensated (C_C=C_0), it has not disappeared: It appears with twice its value in parallel to the source and load termination resistors. Therefore the frequency of minimum attenuation is not exactly equal to the series resonance frequency, and the resonance resistance computed by a formula neglecting C_0 - which is the usual practice - is wrong.

(2) Spurious resonances close to the main response can not be characterized properly. The "dB" or "differential dB" values cannot be directly converted to resistance values or to the motional parameters.

(3) Several problems are related to the hybrid transformer: It must have a flat frequency response, low winding capacitance, low stray inductance, perfect coupling and symmetry over a wide frequency range. Because this critical part is not commercially available, it suffers from poor reproducibility.

(4) The manual measurement is very time-consuming, as it is necessary to sweep in the vicinity of each resonance very slowly to achieve sufficient accuracy.

The disadvantages in item (3) can be overcome, if the hybrid transformer is replaced by a commercially available 180° hybrid coupler embedded in a 50 Ω environment, as proposed in [4]. This however does not eliminate the above mentioned problems (1),(2) and (4).

Stronger responses can also be measured by the conventional π-network method, however the measurement error increases, the weaker the spurs are and the closer to the main mode they are.

5. Alternative measurement methods

The measurement technique to be proposed is based on a test set-up with network analyser or equivalent, the π-network according to IEC 444 and the error correction technique described in [5] and standardized in IEC 444-5. The same method can also be used in conjunction with a s-parameter test system and adequate crystal test fixture.

Step 1: Calibration with short, open and reference resistor in the frequency range of interest

Step 2: Measurement of the static capacitance according to IEC 444-5

Step 3: Determination of the resonance frequency f_r (resp. series resonance frequency f_s, or load resonance frequency f_L) and the equivalent parameters R_1, C_1(and L_1, Q_1) of the main mode with one of the error-corrected methods described in IEC 444-5. If spurious modes are very close to the main mode (i.e. closer than $f_s/1000$), the values derived herewith may include non-negletable errors, but can be used as starting values for the iterative procedure described later.

Step 4: Fast sweep (approximately 1 sec) through the frequency range of interest upwards (increasing frequency) and downwards. A minimum of 500 data points is recommended. Substract the error terms, compute $Y_{up}(f)$ and $Y_{down}(f)$. Substract the admittance $j\omega C_0$ from both sets.

Step 5: Inspect the data and select computationally the peaks with a given minimum (trigger) value Y_{min}. Average the related peak frequencies of both sweeps. This yields an excellent guess for the resonance frequencies of the spurs. The sensitivity of the peak selection can be improved by mathematical differentiation of the Y(f) values. Alternatively the network analyser's internal "peak search" function can be used if implemented.

Step 6: Zoom each spurious response individually and measure Y(f) with higher frequency resolution.

The following steps depend on the type of spur to be considered (see classification in clause 2).

case A (strong spur well "isolated" from the main mode)

Zoomed data points can be selected as in IEC 444-5. Fastest approach is the iterative procedure as desribed in [5]. From a minimum of two or three test frequencies the i-th spurious resonance can be characterized by f_i, R_i, C_i (and L_i,Q_i).

case B (weak spur well "isolated" from the main mode)

Method as in case A. To improve sensitivity, the following modifications could be considered:

- averaging of several sweeps
- reduced RF bandwidth and video bandwidth (slower speed !)
- use of frequency selective, low noise network analyser. The technique using direct measurement of amplidue and phase is in this respect advantageous over the s-parameter systems.
- increase impedance R_T "seen" by the crystal in the test fixture. The s-parameter fixture with its R_T = 100Ω is advantageous over the IEC 444 π-network (R_T = 25Ω).

case C (strong spur in the vicinity of the main mode)

Data are zoomed with high frequency resolution in an interval covering the 3dB-bandwidth of the main mode and of the considered spur (its bandwidth is assumed to be approximately equal to that of the main mode - as is its Q in most cases).The parameters of both modes are then extracted by a parameter-fitting algorithm.

For uncoupled modes the equivalent circuit diagram of Fig.3 is used, i.e. three variables per resonance have to be determined (L_i, C_i, R_i or f_i, C_i, R_i). For coupled modes one circuit of Fig.4 has to be used. For N resonances 3 + 4•(N-1) elements have to be determined.

Rather good starting values for the elements can be used which speeds up the parameter search and reduces the risk of ill-conditioned iterations to wrong local minima.

These are:

f_1, R_1,C_1 (and therefore L_1 and Q_1) of the main mode from step 3

f_2 from the location of the peak maximum of Y(f) (after removal of $j\omega C_0$)

R_2 from the amplitude of the peak maximum, derived from

$$R_2 \approx \frac{1}{|Y(f_{peak})|}$$

C_2 from the assumption that the Q_2-value of the spur is approximately the same as Q_1 of the main mode

$$C_2 \approx \frac{1}{\omega_2 Q_2 R_2}$$

In the case of coupled modes, the starting value of element which determines the coupling can be arbitrarily set to zero.
The iteration procedure minimizes the error function

$$E = \Sigma w_i \, |Y_i - Y_i^M|^2 = \Sigma w_i \, ((G_i - G_i^M)^2 + (B_i - B_i^M)^2)$$

in which $Y_i = G_i + j\,B_i$ denotes the theoretical values from circuit analysis computed at the measurement frequency f_i, and $Y_i^M = G_i^M + j\,B_i^M$ represents the values derived from the measurement at f_i. The weighting factors w_i can be selected such, that the data points close to the resonances get the greatest significance, e.g. $w_i = |Y_i^M|$.
Several searching algorithms for minimization of E are applicable. One of them (Newton method) is described e.g in [9]. Another approach is the method of steepest descend, e.g. the Simplex algorithm. The evaluation of the different methods with respect to simplicity and stability is currently under progress.

case D (weak spur in the vicinity of the main mode)
The method is identical to case C, except that the starting value of R_2 hass to be derived differently, because the amplitude of the spurious peak is too erraneous, as it is located on the slope of the main resonance curve.
A more reliable starting value for R_2 is gained as follows:
The approximate admittance of the main mode

$$Y_m(f_i) = \frac{1}{R_1 + j\frac{1}{\omega C_1}\left(\frac{\omega^2}{\omega_1^2} - 1\right)}$$

is computed at the measurement frequencies f_i by using the starting values of f_1, C_1, R_1. It is then substracted from the measured admittance values Y_i^M in the vicinity of the main mode and the weak spur. From the peak of this residual Y_{spur} the starting value of R2 can be computed as

$$R_2 = \frac{1}{|\max(Y_{spur})|}$$

It should be noted, that the achievable accuracy for the parameters of very weak spurs is reduced. However, the method proposed herein is superior to the conventional methods used so far.

6. Conclusions

The paper describes a concept for the measurement of spurious resonances, which allows the use of network analysers in conjunction with error correction techniques. The test fixture can be the π-network or the s-parameter test fixture as described in IEC 444-5. The proposal includes the determination and characterization of weak spurs,which may lie close to a strong mode. It considers also the mechanical coupling of modes. The next steps are the optimization of the parameter fitting algorithm. The experimental verification and comporative measurements have to follow. These results will be reported later.

7. Acknowledgements

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8. References

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