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Measurement of quartz crystal unit parameters –

Part 9: Measurement of spurious resonances of piezoelectric crystal units

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MEASUREMENT OF QUARTZ CRYSTAL UNIT PARAMETERS –

Part 9: Measurement of spurious resonances of piezoelectric crystal units

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The text of this standard is based on the following documents:

FDIS	Report on voting
49/764/FDIS	49/774/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of IEC 60444 series, published under the general title *Measurement of quartz crystal unit parameters,* can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
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A bilingual version of this standard may be issued at a later date.

MEASUREMENT OF QUARTZ CRYSTAL UNIT PARAMETERS –

Part 9: Measurement of spurious resonances of piezoelectric crystal units

1 Scope

This part of IEC 60444 describes two methods for determining the spurious (unwanted) modes of piezoelectric crystal resonators. It extends the capabilities and improves the reproducibility and accuracy compared to previous methods.

The previous methods described in IEC 60283 (1968) were based on the use of a measuring bridge, which applies to non-traceable components such as variable resistors and a hybrid transformer, which are no longer commercially available.

Method A (Full parameter determination)

Full parameter determination allows the determination of the equivalent parameters of the spurious resonances and is based on the methods described in IEC 60444-5 using the same measurement equipment. It is the preferred method, which can be applied to the measurement of low and medium impedance spurious resonances up to several kΩ.

Method B (Resistance determination)

Resistance determination should be used for the determination of high impedance spurious resonances as specified, for example for certain filter crystals. It uses the same test equipment as method A in conjunction with a test fixture, which consists of commercially available microwave components such as a 180° hybrid coupler and a 10 dB attenuator, which are well-defined in a 50 Ω environment. This method is an improvement to the “reference method” of the obsolete IEC 60283.

2 Overview

Piezoelectric crystal units show multiple resonances, which can be electrically represented by a parallel connection of a number of series resonant circuits. The one-port equivalent circuit of the complete crystal unit is shown in Figure 1 (taken from IEC 60444-5).

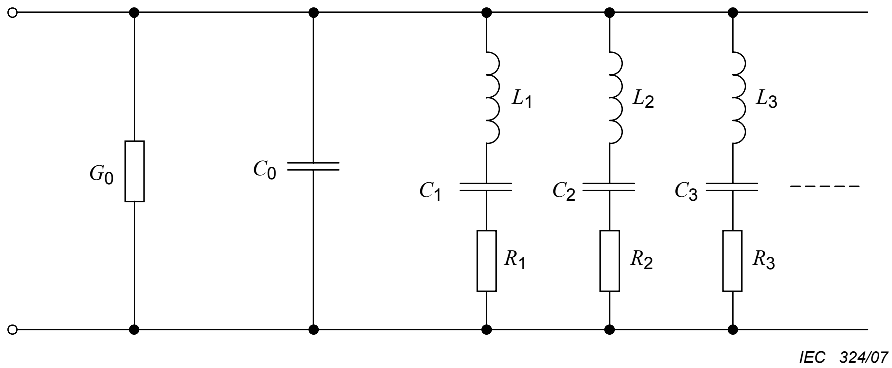

Figure 1 – General one-port equivalent circuit for multiple resonances

The total admittance Y_{tot} of the equivalent circuit for n resonance modes is therefore

$$Y_{tot} = G_0 + j\omega C_0 + \sum_i Y_i \tag{1}$$

with

$$Y_i = G_i + jB_i = \left(R_i + j\omega L_i + \frac{1}{j\omega C_i} \right)^{-1} \qquad (i = 1,2,\ldots n) \tag{2}$$

Index i = 1 represents the main mode, while i = 2 … n represents the spurious resonance modes.

The spurious modes are regarded as uncoupled modes. Coupled modes can also be found by the described test methods, however their strong amplitude dependence does not allow for the precise determination of their parameters.

The attenuation a^i_{spur}, of a spurious mode i, is defined as the logarithmic ratio (expressed in dB) of its resistance R_i, to the resistance R_1 of the main mode:

$$a^i_{spur} = 20 \cdot \log_{10}\left(\frac{R_i}{R_1}\right) \tag{3}$$

Figure 2 shows a typical spectrum for the spurious resonances of an AT-cut quartz crystal unit as displayed on a spectrum analyzer using a π-network according to IEC 60444-1.

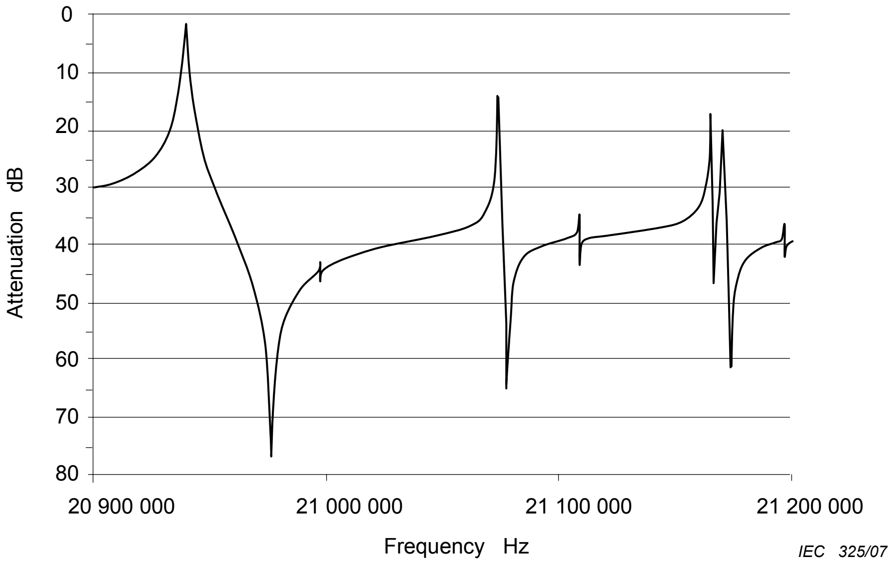

Figure 2 – Spectrum of spurious responses

NOTE The attenuation values measured on a network analyzer depend on the termination resistance of the test fixture used (e.g. 25 Ω for a *π*-network of IEC 60444-1). They are different from the spurious attenuation as computed from equation (3).

NOTE The frequencies and attenuation values measured on a network analyzer are different if the crystal resonator is connected to a load capacitor.

See also note under 3.2.1.2.

3 Measurement methods

The following measurement parameters are necessary and should be given in the detail specification:

- frequency range of the spurious resonances FR_{spur} to be evaluated;
- level of drive.

Care must be taken in selecting a suitable measurement (sweep) time.

3.1 Method A (Full parameter determination)

The measurement system consists of a *π*-network or an s-parameter test fixture in accordance with IEC 60444-1 and IEC 60444–5 in conjunction with a network analyzer or an equivalent setup.

The admittance of the crystal is measured within the specified frequency range FR_{spur}. The spurious resonances are isolated with the method of successive removal of resonances. From the admittance data, the equivalent circuit parameters of the various resonance modes are computed using one of the evaluation procedures described in IEC 60444-5.

3.1.1 Measurement procedure

The technique is described in more detail in [1][1]. The measurement sequence is as follows:

a) measurement of the static capacitance C_0 as in IEC 60444-5;

[1] Figures in square brackets refer to the bibliography.

b) measurement of the main mode parameters (i = 1) as in IEC 60444-5, the resulting parameters are:

series resonance frequency $f_s = f_1 = \frac{\omega_1}{2\pi}$

equivalent electrical parameters R_1, C_1, and L_1, and

$$\text{quality factor } Q = Q_1 = \frac{\omega_1 L_1}{R_1} = \frac{1}{\omega_1 C_1 R_1} \tag{4}$$

c) measurement of the complex admittance $Y_{res}(f)$ in the specified frequency range FR_{spur}

Measurement parameters:

Assuming

$$Q_2, Q_3, \ldots Q_n \approx Q_1 \tag{5}$$

the minimum settling time t_{set} for each frequency is:

$$t_{set} = \frac{Q_1}{\omega_1} \tag{6}$$

For at least two data points within the resonance bandwidth, the minimum number of data points N is

$$N = 2 \cdot \frac{FR_{spur}}{Q_1} \tag{7}$$

The minimum sweep time t_{swp} is then

$$t_{swp} = t_{set} \cdot N \tag{8}$$

NOTE If necessary the frequency sweep range FR_{spur} must be divided into several sub-intervals.

Resulting parameters:

The array of complex admittance $Y_{res}(f)$, expressed, for example as arrays for magnitude $|Y_{res}(j)|$, phase $\Phi_{res}(j)$ and frequency $f(j)$ with j = 1,2, … N and $f(1) = f1$, the frequency of the main mode.

Search for spurious resonance peaks

The search for spurious resonances requires several steps to distinguish the resonance peaks from noise peaks and from broadband responses.

See flowchart in Figure 3 for reference.

– Identify local maxima of $\mathrm{Re}(Y_{res}(j))$ for neighbouring data points (j –1, j, j +1)

For the analysis the real part of the admittance is used.

$$\mathrm{Re}(Y_{res}(j)) = |Y_{res}(j)| \cdot \cos(\Phi_{res}(j)) \tag{9}$$

For $j = 2 \ldots N-1$ the admittance values are analysed as follows:

If

$$\mathrm{Re}(Y_{res}(j)) > \mathrm{Re}(Y_{res}(j-1)) \text{ and } \mathrm{Re}(Y_{res}(j)) > \mathrm{Re}(Y_{res}(j+1))$$

then

$f_{peak} = f(j)$ is a candidate for a spurious resonance peak.

– Distinguish between real peaks and fake peaks

Fake peaks due to noise, etc. can be identified by assuming a realistic Q-value for the spurious resonances with respect to Q_1 as determined in step b).

Upper limit Q_{max}:

$$Q_{max} = k_{max} \cdot Q_1 \quad \text{with } k_{max} = 2 \ldots 10 \ \text{(recommended: } k_{max} = 5) \tag{10}$$

The minimum 3 dB half-bandwidth BW_{min} for a spurious resonance peak is therefore

$$BW_{min} = \frac{f_1}{2 \cdot Q_{max}} \tag{11}$$

For each candidate for a spurious resonance peak, the data points next to $|Y_{res}(f_{peak})|$ are inspected. If the amplitude at each side is less than according to Q_{max}:

$$\frac{|Y_{res}(f_{peak})|}{|Y_{res}(f_{peak} \pm BW_{min})|} \leq \sqrt{2} \tag{12}$$

then this peak is still accepted as a candidate. Otherwise, the peak is considered as a fake.

Lower limit Q_{min}:

$$Q_{min} = k_{min} \cdot Q_1 \quad \text{with } k_{min} = 0{,}1 \ldots 0{,}5 \ \text{(recommended: } k_{min} = 0{,}2) \tag{13}$$

The maximum 3 dB half-bandwidth BW_{max} for a spurious resonance peak is therefore

$$BW_{max} = \frac{f_1}{2 \cdot Q_{min}} \tag{14}$$

For each candidate for a spurious resonance peak , the data points next to $|Y_{res}(f_{peak})|$ are inspected. If the amplitude at each side is greater than according to Q_{max}:

$$\frac{|Y_{res}(f_{peak})|}{|Y_{res}(f_{peak} \pm BW_{max})|} \geq \sqrt{2} \tag{15}$$

then the selected peak is accepted as a true spurious resonance peak. Otherwise, the peak is considered as a fake.

Resulting parameters: n–1 spurious resonance frequencies f_m^i (i = 2 … n)

NOTE If the spurious resonances are very close to strong modes, it is recommended that a 1 dB instead of a 3 dB bandwidth is used. In the above equations, the term $\sqrt{2}$ must then be replaced by the factor 1,122, and the values for BW_{max} and BW_{min} must be changed accordingly.

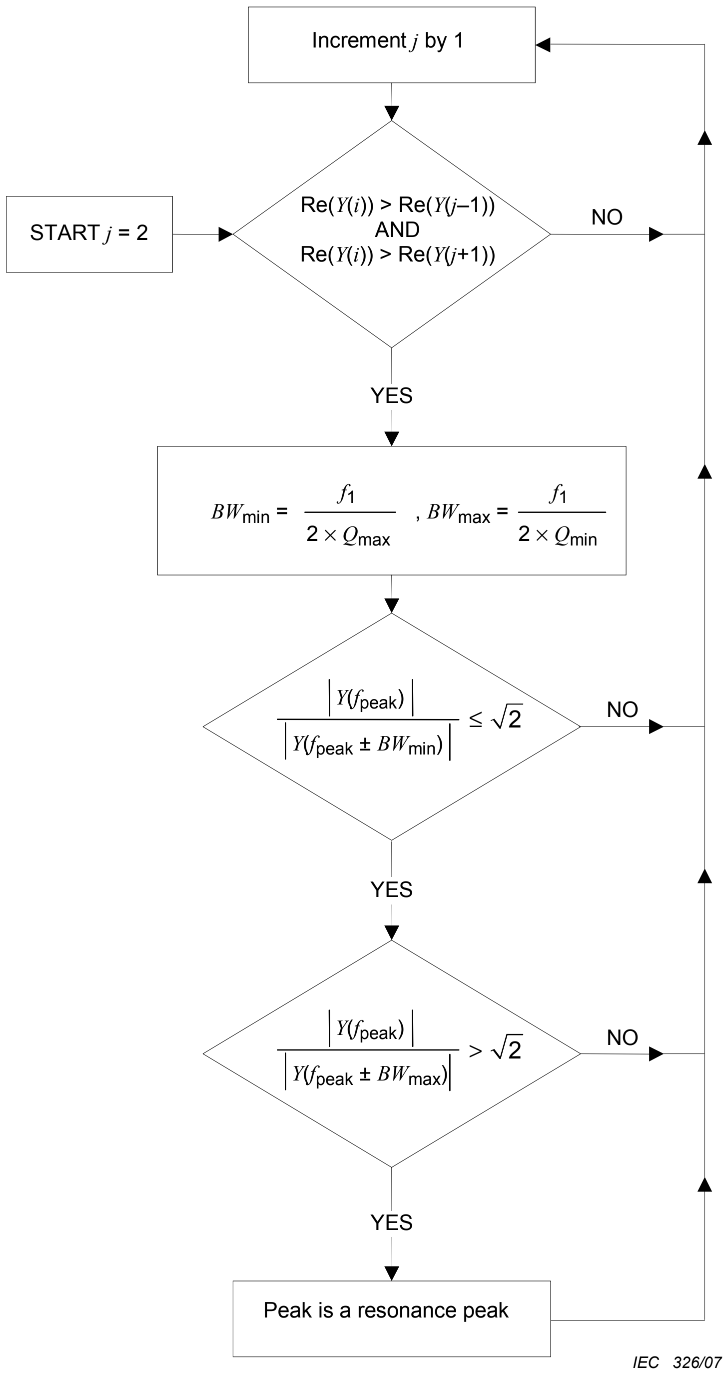

Figure 3 – Flowchart for spurious resonance search

d) zooming of the identified spurious resonances

For each of the true spurious peaks f_{spur}(i) identified in step c) a new set of admittance data is taken by zooming the frequency intervals $f_{spur}(i) \pm BW_{max}$ with at least N_i = 11 data points per sweep interval and a minimum sweep time t_{swp} of

$$t_{swp} \geq \frac{10 \cdot \sqrt{Q_{min} \cdot Q_{max}}}{k_{min} \cdot \omega_1} \qquad (16)$$

Resulting parameters:

Arrays of admittances for each spurious resonance $Y^{i}_{raw}(f)$, expressed by the arrays of amplitude $\left|Y^{i}_{res}(j)\right|$, phase $\arg(Y^{i}_{res}(j))$, and frequency $f^{i}(j)$ with i = 2 … n and j = 1... 11

e) removal of the admittances of the main mode (i = 1) and of C_0

From each set of raw admittances $Y^{i}_{raw}(f)$ the contribution of the main mode and of the static capacitance C_0 are subtracted.

$$Y^{i}_{res}(f) = Y^{i}_{raw}(f) - Y_1(f) - Y_0(f) \qquad (i = 2 \dots n) \tag{17}$$

with

$$Y_1(f) = \left(R_i + j\omega L_i + \frac{1}{j\omega C_i}\right)^{-1} \tag{18}$$

$$Y_0(f) = j\omega C_0 \tag{19}$$

$$\omega = 2\pi f \tag{20}$$

Resulting parameters:

Arrays of admittances for each spurious resonance $Y^{i}_{res}(f)$, expressed by the arrays of amplitude $\left|Y^{i}_{res}(j)\right|$, phase $\arg(Y^{i}_{res}(j))$, and frequency $f^{i}(j)$ with i = 2 … n and j = 1... 11

f) Calculation of the series resonance frequency and the equivalent parameters of the strongest (remaining) mode

The strongest (remaining) mode is selected. This is the k^{th} mode, in which the maximum value of the real part given by

$$\max\left(\mathrm{Re}\left(Y^{i}_{res}(f)\right)\right)$$

is largest.

Calculation for the series resonance frequency f^{k}_{s}, the motional parameters R_k, C_k, and L_k, and the Q-factor Q_k from $Y^{k}_{res}(f)$ are given in IEC 60444-5.

Resulting parameters:

Series resonance frequency f^{k}_{s}, motional parameters R_k, C_k, L_k, and Q_k of strongest (remaining) mode.

NOTE If the settling time computed from

$$t^{k}_{set} = \frac{Q_k}{2\pi f^{k}_{s}} \tag{21}$$

is larger than $\frac{t_{swp}}{N_i}$ (see equation (16)), then the measurement of that spurious mode must be repeated with an accordingly corrected sweep time.

g) Removal of the evaluated spurious resonance

From all remaining sets of admittances $Y^{i}_{res}(f)$ the contribution of the k^{th} spurious mode evaluated in *f*) is subtracted.

$$Y_{res}^{i}(f) := Y_{res}^{i}(f) - Y_k(f) \qquad (i = 2 \ldots n,\ i \neq k) \qquad (22)$$

with

$$Y_k(f) = \left(R_k + j\omega L_k + \frac{1}{j\omega C_k}\right)^{-1} \qquad (23)$$

and $Y^{i}_{res}(f)$ is replaced by the result of the next iteration.

h) Continue with step g) for all remaining spurious resonance

i) Evaluation of the validity of the analysis (optional)

From the parameters of all determined spurious resonance modes and the main mode the total admittance Y_{tot} can be computed as

$$Y_{tot}(f) = \sum_{i=1}^{n}\left(R_i + j2\pi f L_i + \frac{1}{j2\pi f C_i}\right)^{-1} + j2\pi f C_0 \qquad (24)$$

and compared with the admittance $Y_{res}(f)$ measured in step c).

From the normalized sum of error squares a measure of the quality of data fitting can be derived.

NOTE As all resonances can influence each other, the sum of error squares can be minimized further by variation of the parameters C_0, $f(i)$, R_i, C_i and L_i with $i = 1 \ldots n$.

3.2 Method B (Resistance determination)

The measurement system consists of the same equipment setup as described in IEC 60444-5, but uses a different test fixture, which consists of a 50 Ω, 180° hybrid coupler, a 10 dB attenuator and a variable balancing capacitor. All parts are commercially available components.

Figure 4 shows the electrical circuit diagram of the test fixture. XUT is the crystal under test, C_{bal} is a variable capacitor of 1 ~ 10 pF range. The 50 Ω, 10 dB attenuator is a device having the lowest possible VSWR in the measurement frequency range, which is commercially available from a number of sources. The 180° hybrid coupler (or "two-way 0°/180° power splitter/combiner") is a commercially available device with 50 Ω termination, suitable for the frequency range to be measured. Example: type PSCJ2-1 (Mini-Circuits Laboratory, Brooklyn, N.Y.) for 1 MHz up to 200 MHz.

The mechanical layout of the test fixture must take into account the principles of RF engineering with low stray capacitances and good shielding between input and output.

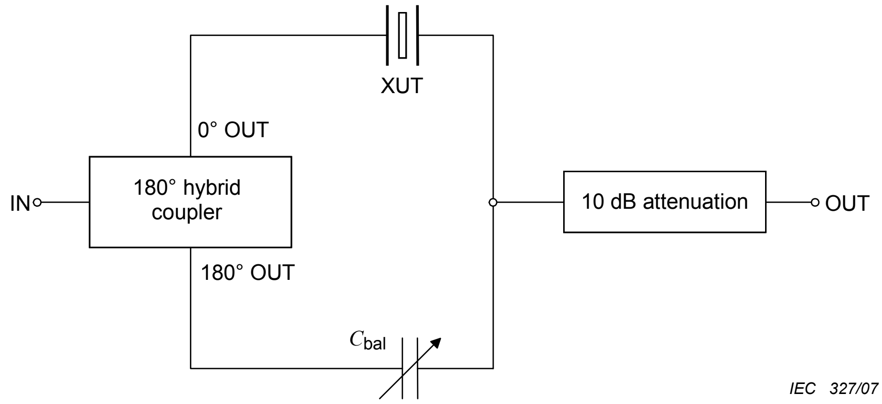

Figure 4 – Electrical diagram of the test fixture for method B

NOTE For automatic operation the variable capacitor can be replaced by two varactor diodes of suitable C(V) characteristics, which are connected in anti-series and biased accordingly.

3.2.1 Measurement procedure

3.2.1.1 Initial calibration

The RF output level of the generator at the input port must be adjusted so that the maximum drive level specified is not exceeded.

– Short

Insert a short at the XUT ports. Set C_{bal} to its minimum capacitance value.

Read complex output voltage U_{S}

– “Open” balancing

Insert a small capacitor C_{open} of about 2 pF to 5 pF at the XUT port, set C_{bal} to minimum and read complex output voltage $U_{0.}$ The output amplitude should be at least 60 dB lower than the short-circuit output voltage

$$20 \cdot \log_{10}\left(\frac{|U_S|}{|U_0|}\right) \geq 60 \tag{25}$$

– Reference

Add a reference resistor R_{ref} of 50 Ω or 100 Ω at the XUT port in parallel to C_{open}.

Read complex output voltage $U_{\mathrm{ref.}}$

From the complex output voltages U_{S} and U_{ref} compute the (complex) fixture impedance R_{T}

$$R_T = \frac{R_{ref}}{\left(\frac{U_S}{U_{ref}} - 1\right)} \tag{26}$$

$|R_{\mathrm{T}}|$ should be in the order of 100 Ω ± 10 %

NOTE In the following, evaluations of the phase measurements are disregarded, only the amplitude measurements are considered.

3.2.1.2 Response measurement

– Initial balancing

With the crystal unit under test inserted, set the sweep frequency range to about ±500 kHz or wider. Tune the variable capacitor C_{bal} for an overall symmetric response shape as depicted in Figure 5.

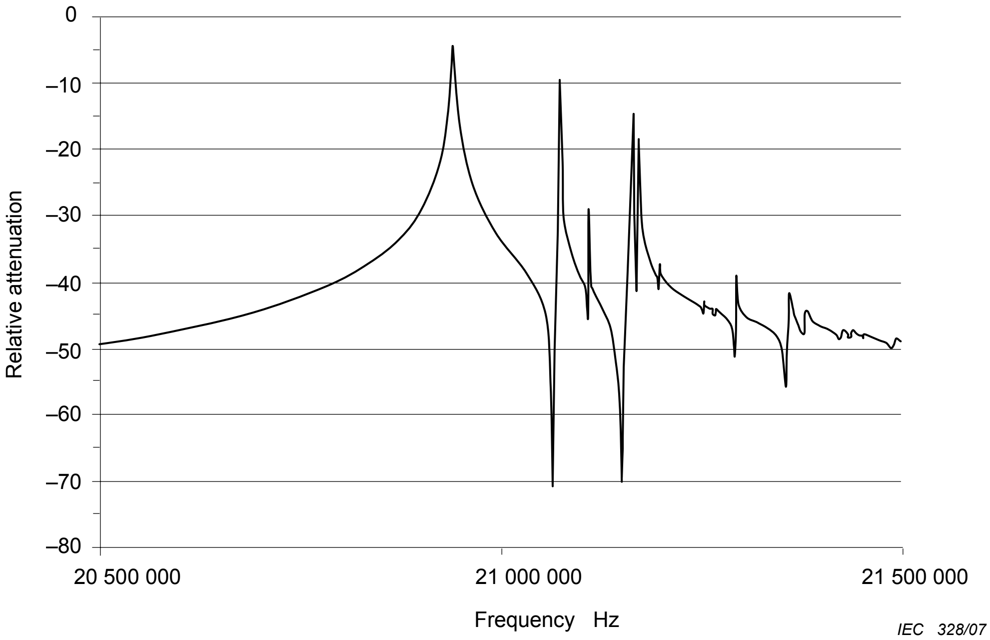

Figure 5 – Balanced setting of C_{bal} yields a symmetric frequency response

– Measurement with visual aid

Scan the specified frequency range FR_{spur}. The sweep time should be as derived in equations (6) to (8). Inspect visually the amplitude spectrum of spurious resonance peaks. For more accurate evaluation, the frequency range of individual spurious responses may be zoomed on the display. The sweep time of the sub-intervals should also be according to equation (8)

a) Strong spurious resonance modes

For spurious resonance peaks which are well-separated from adjacent responses, and which are at least 20 dB above the bottom line, the (maximum admittance) frequency f_m^i is located at the peak voltage U_m^i and the (maximum admittance) resistance R_m^i can be evaluated as

$$R_m^i = R_T \cdot \left(\frac{U_S}{U_m^i} - 1 \right) \tag{27}$$

If the amplitude is given as attenuation in dB relative to the reference calibration with R_{ref}, then the (maximum admittance) resistance R_m^i is determined from a_{ref}^i as

$$R_m^i = 10^{\frac{a_{ref}^i}{20}} \cdot \left(R_T + R_{ref} \right) - R_T \tag{28}$$

In most cases it is sufficient to use the magnitude values of R_T, U_S and U_m^i instead of their complex values.

b) Weak spurious resonance modes

For weak spurious resonance modes, which show a differential response of less than 20 dB in the initial balance setting, the setting of C_{bal} has to be modified. Tune C_{bal} in such a way that the bottom line around the considered spurious resonance peak is shifted to a minimum value. The two sides of the peak response should then have a symmetrical shape as shown in Figure 6. This rebalancing of C_{bal} eliminates capacitive or inductive influences of neighbouring resonance modes (both main and spurious).

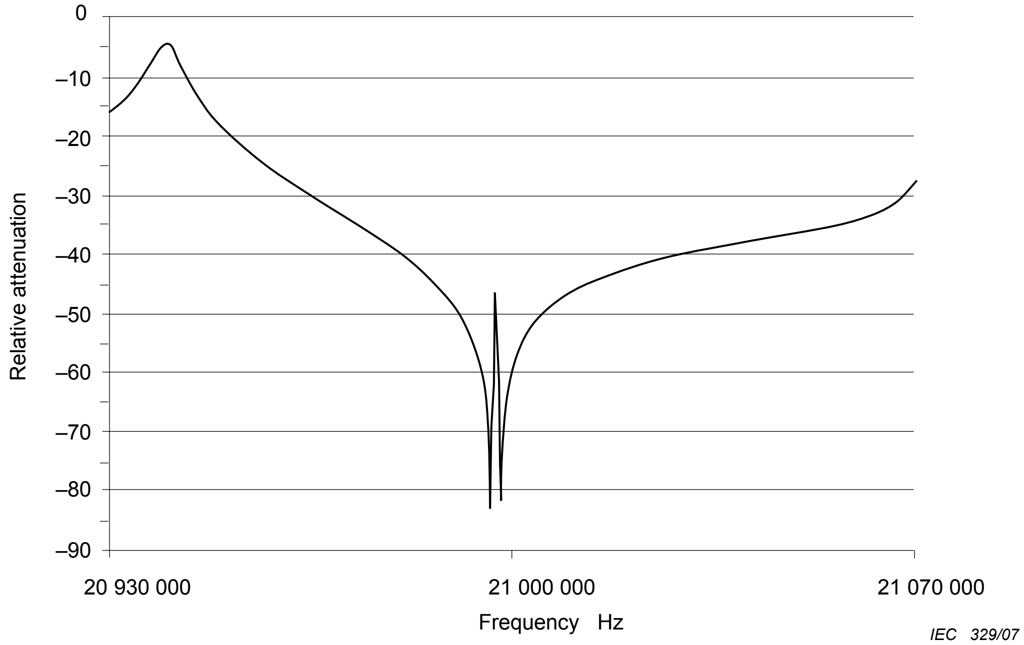

Figure 6 – Setting of C_{bal} for a weak spurious mode

The (maximum admittance) frequency f_m^i of the spurious resonance mode is located at the peak voltage U_m^i and the (maximum admittance) resistance R_m^i can be evaluated from equation (27) or (28).

NOTE The attenuation of the spurious resonance peak with respect to the main mode, which is observed on the test equipment is given by

$$a_{meas}^i = 20 \cdot \log_{10}\left(\frac{R_i + |R_T|}{R_1 + |R_T|}\right) \tag{29}$$

This value is different from the spurious attenuation as defined in equation (3), as can be seen by direct comparison.

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[1] NEUBIG B.W., *Recent Advances In The Measurement of Spurious Resonances Of Crystal Units*, Proc. Of the 9th European Frequency and Time Forum (EFTF), Besançon, pp.469-472 (1995)

[2] SCHULZKE L. *Private communication*

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