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Error-Corrected Measurement of High Frequency Quartz Crystal Units based on IEC Publication 60444-5

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Content

- Brief History of Publication IEC 60444-5
- Equivalent Circuits of Quartz Crystal Units
- Measurement Methods
  - Traditional Measurement of IEC 60444-1+2
  - Measurement Methods of IEC 60444-5
- Test Fixtures and Calibration
- Error Corrections
- Algorithms for Parameter Evaluation
- Discussion

Brief (incomplete) History of IEC 60444-5

- First publications proposing error correction methods based on s-parameters in 1984-1985, e.g.:
  - Aubry, J.P. et al.: S.Y . Parameter method for accurate measurement … up to 2 GHz; 37th Annual Frequency Control Symposium (1983)
  - Smith, W.L.: An overview of a proposed standard method for the measurement … up to 1 GHz; 6th Quartz Crystal Devices Conference, Kansas City (1984)
  - Smith, W.L.: EIA Standard 512: Some further discussion and comment; 7th Quartz Crystal Devices Conference, Kansas City (1985)
  - Peach, R.C.: Morris, S.E.: A system for precision measurement …; 39th Annual Freq. Control Symposium (1985)
  - Williamson, R.J,: An Improved Method for Measuring … IEEE Trans. UFFC (1987)
- TC49 WG6 meeting 04~06 March 1986 in London
  - Peach, R.C. et al.: Proposal for UK Standard: A Reference method of Measurement for Quartz Resonator units… between 1 kHz and 1 GHz
- Publications proposing error correction methods for fast measurement based on direct transmission (IEC 60444-1)
  - Neuscheler, F.: Schwingquarz-Daten mit Netzwerk-Analysatoren gemessen; Elektronik (1987)
  - Neubig, B.: Measurement of Quartz Crystal Units up to 500 MHz and above…; 11th Quartz Crystal Devices Conference Kansas City (1989)

Brief (incomplete) History of IEC 60444-5

- **TC49 WG 6 Workshop Meeting 17~21 October 1988 in Bled (former Yugoslavia)**
  - **Scope: Program of measurements agreed in London, 49(Sec)182**
  - **Comparison of the performances of a variety of measurement systems using a set of test crystals:**
    - 1 MHz (SL-cut)
    - 5 MHz 3rd O/T
    - 20 MHz fund
    - 81 MHz 5th O/T
    - 125 MHz fund
    - 175 MHz 5th O/T
    - 200 MHz 5th O/T
    - 300 MHz fund
    - 314 MHz fund
    - 375 MHz 3rd O/T
    - 600 MHz fund
    - 943 MHz 3rd O/T
  - **Software Systems**
    - UK S-parameter
    - US S-parameter
    - UK π-network
    - German π-network (classical)
    - German π-network (extended)
  - **Test fixtures**
    - UK S-parameter
    - US S-parameter
    - UK π-network
    - German π-network (coaxial)
    - German π-network (thick film)
    - Yugoslav S-parameter (reflection)
  - **Test equipment**
    - HP 3577A Network analyzer
    - HP 8753A Network analyzer
    - Rohde & Schwarz ZPV Vector analyzer + SMPD Signal generator

Brief (incomplete) History of IEC 60444-5

- Conclusions
  - All systems give a high level of reproducibility, within 0.1 ppm in frequency (f_s) and 0.1% in resistance (R_1) and motional capacitance (C_1)
  - Systematic variations exist between different software systems and test fixtures due to the impact of lead inductance and resistance
  - None of the systems emerged as being clearly superior
  - Direct Transmission Technique proved to show comparable results to S-parameter based methods
- IEC Documents
  - …
  - 49(CO) 248 (Draft International Standard)
  - 49(CO)268 (Voting Report)
  - 60444-5 Ed.1 (1995)

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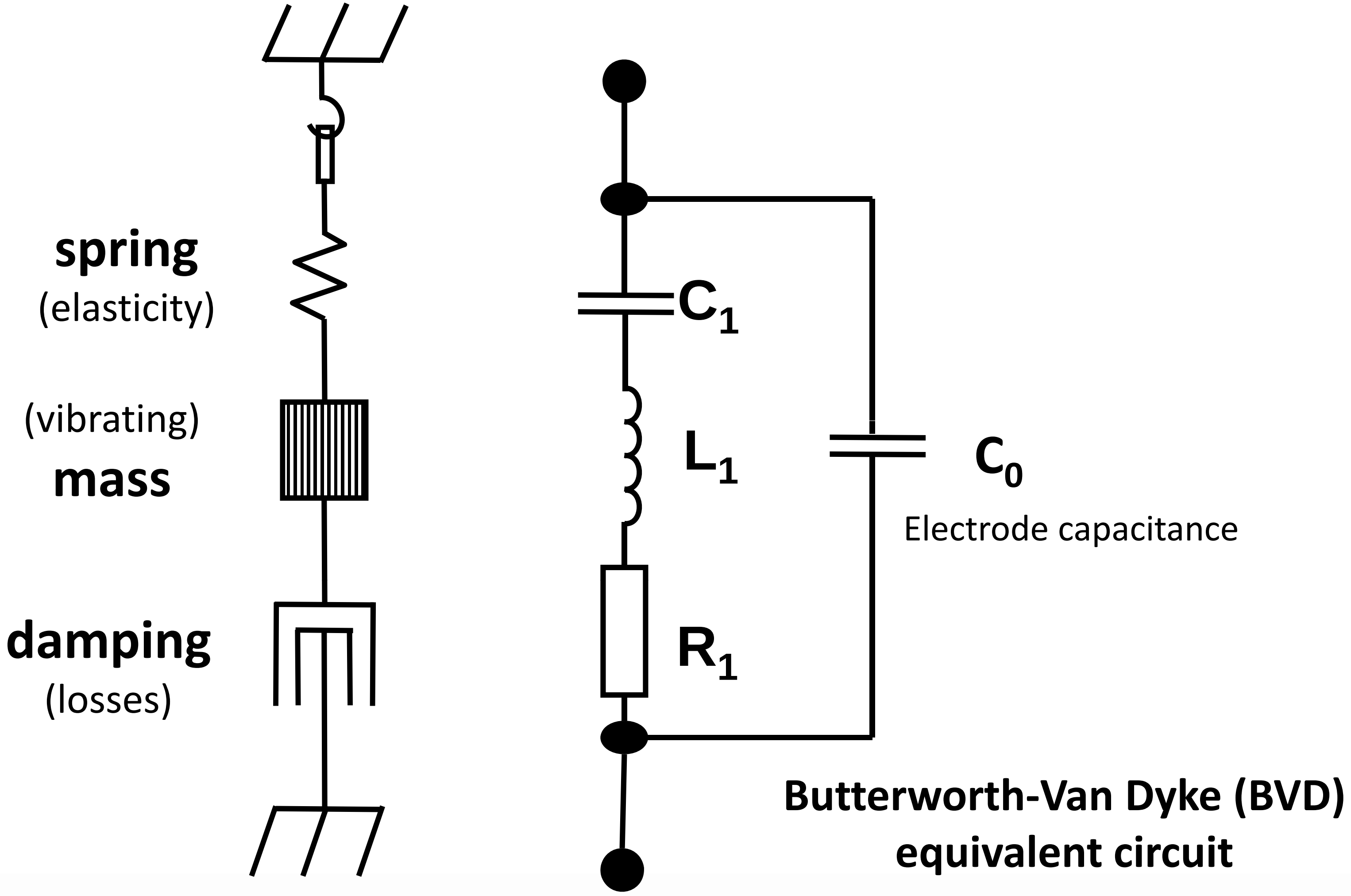
Mechanical vs. Electrical Equivalent



spring
(elasticity)

(vibrating)
mass

damping
(losses)

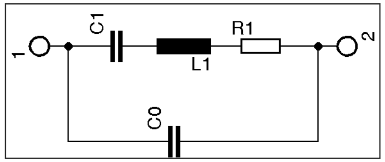
Electrode capacitance

Butterworth-Van Dyke (BVD) equivalent circuit

Extension of Equivalent Circuit I

- Butterworth-Van-Dyke (BVD): 1-port model

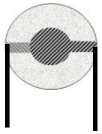
=



$$f_s = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

$$f_p = \frac{1}{2\pi\sqrt{L_1 \frac{C_1 C_0}{C_1 + C_0}}}$$

- Crystal unit with bonds / leads (1-port)



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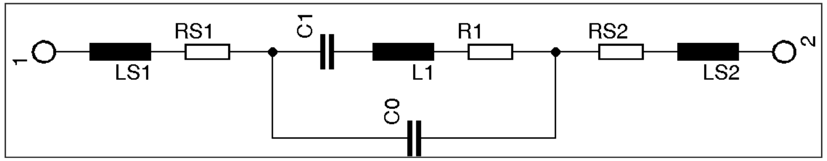
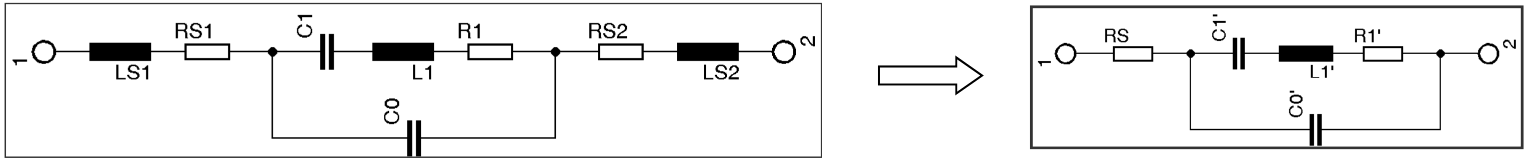


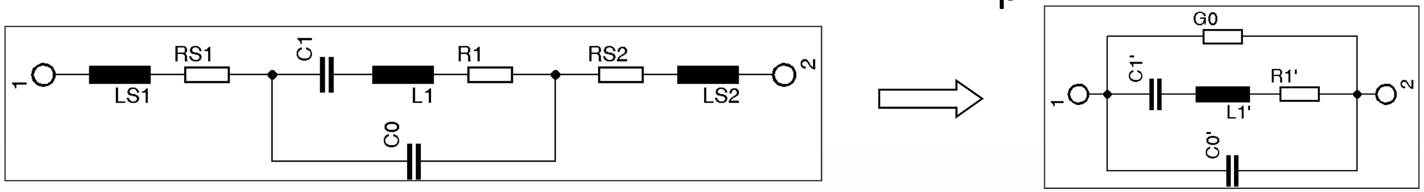
$L_{S1} \approx L_{C2} \approx$ 2 nH ~ 10 nH
Ceramic packages:
$L_{S1} \neq L_{C2}$ und $R_{S1} \neq R_{S2}$

Extension of Equivalent Circuit II

- Crystal unit with bonds / leads (1-port): Transformation with series R_s

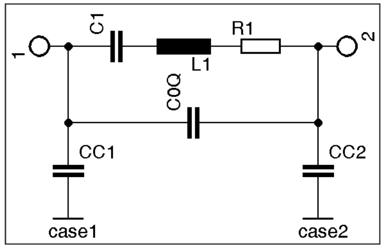


- Crystal unit with bonds / leads (1-port): Transformation with parallel R_p



Extension of Equivalent Circuit I

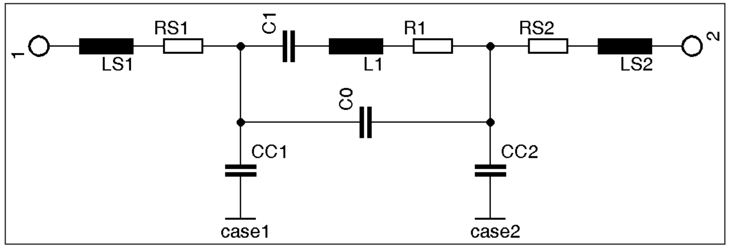
- BVD : Package capacitances added (2-port)



$$C_0 = C_{0Q} + \frac{C_{C1} \cdot C_{C2}}{C_{C1} + C_{C2}}$$

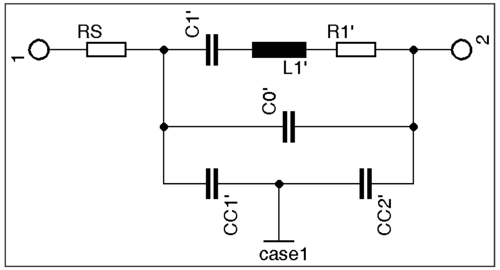
metal package:
$C_{C1} \approx C_{C2} \approx 0{,}5$ pF
ceramic package with metal lid:
C_{C1}(upper) > C_{C2} (downside)

- Crystal unit with package (2-port)

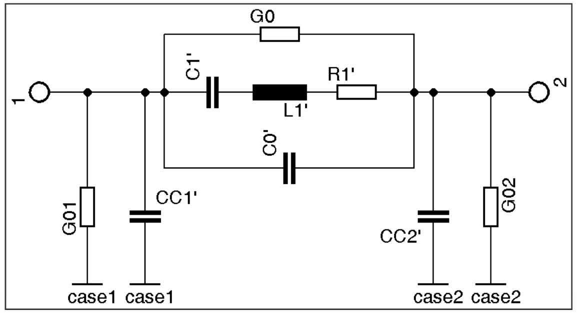


Extension of Equivalent Circuit II

- Crystal unit with package (2-port) - Transformation with R_s

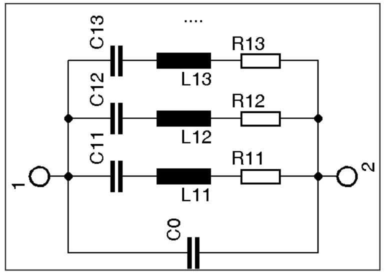


- Crystal unit with package (2-port) - Transformation with R_p



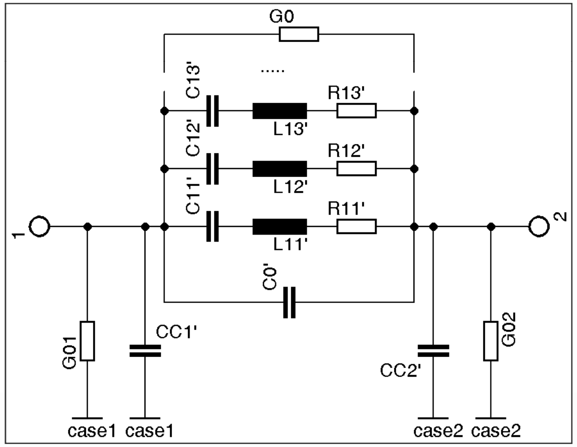
Extension of Equivalent Circuit III

- Crystal unit multiple resonances (1-port)

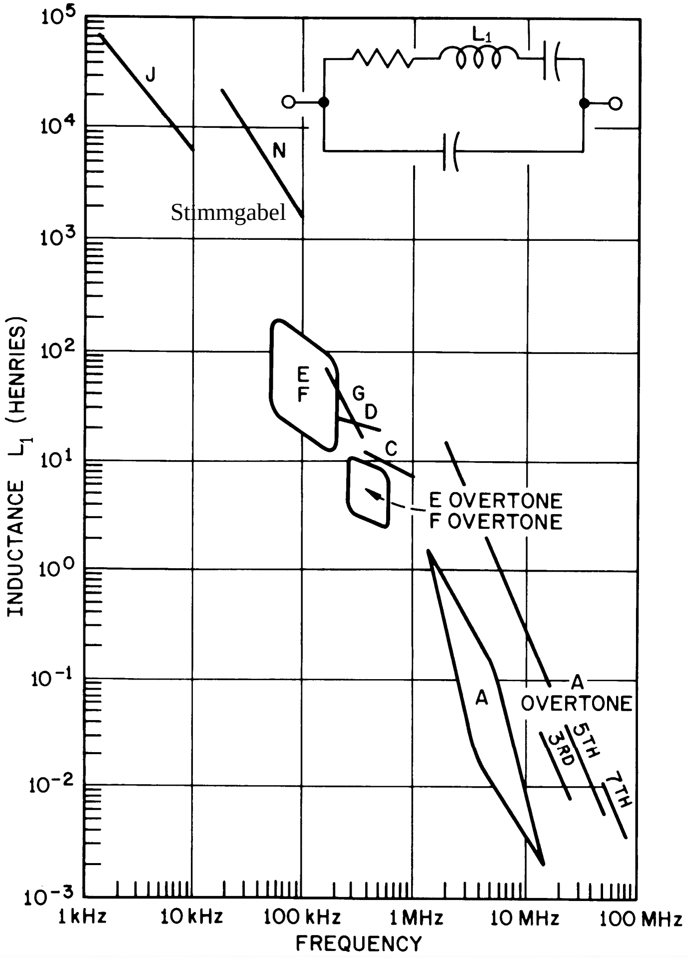


Indices 11 = main mode
Indices 1i = unwanted modes = spurious resonances

- Crystal unit multiple resonances (2-port)



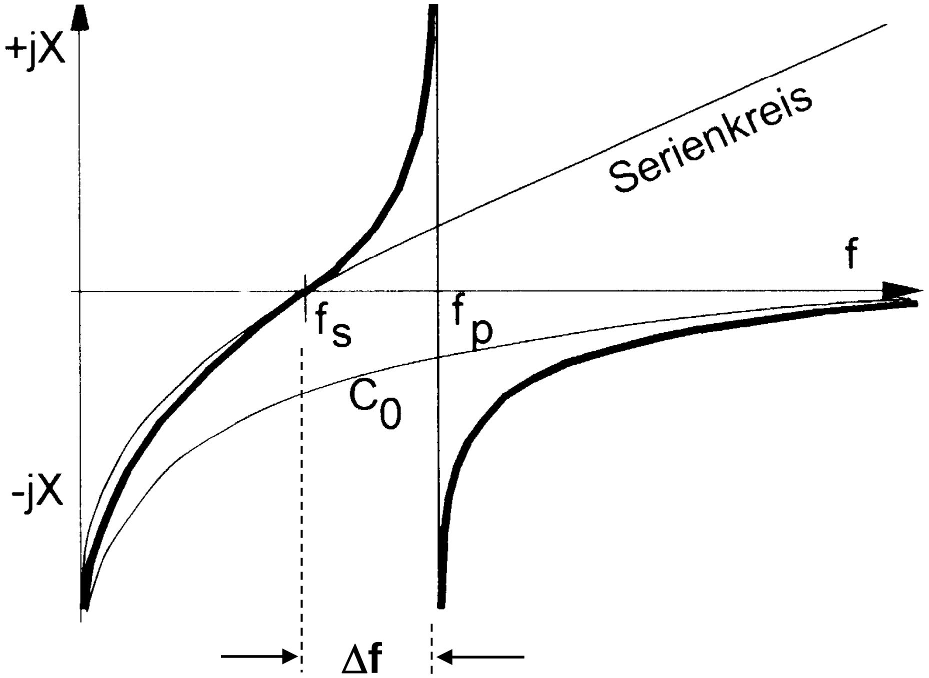
Motional Parameters L_1 vs. C_1

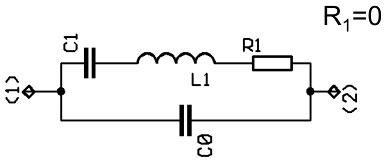


Over a frequency range of 4 decades the value of the dynamic inductance L_1 expands over 4 orders of magnitude.

Dynamic capacitance C_1 is always in the order of … fF, and thus easier to handle

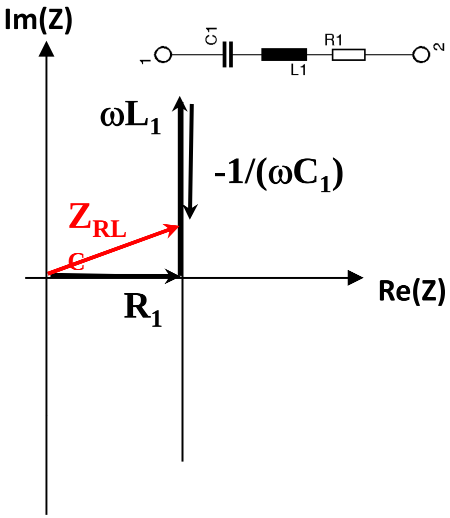
BVD Lossless: crystal reactance jX(f)



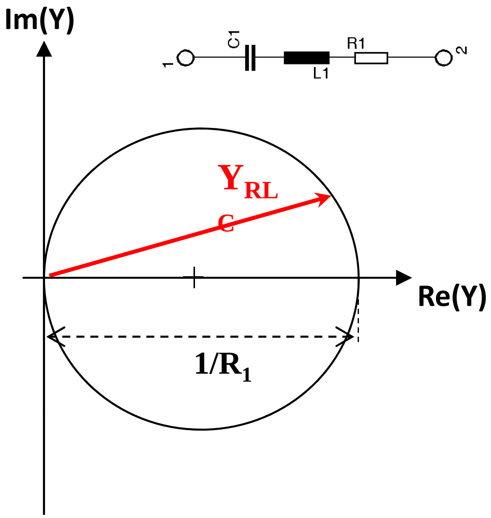


$$\frac{\Delta f}{f_S} \approx \frac{C_1}{2 \cdot C_0}$$

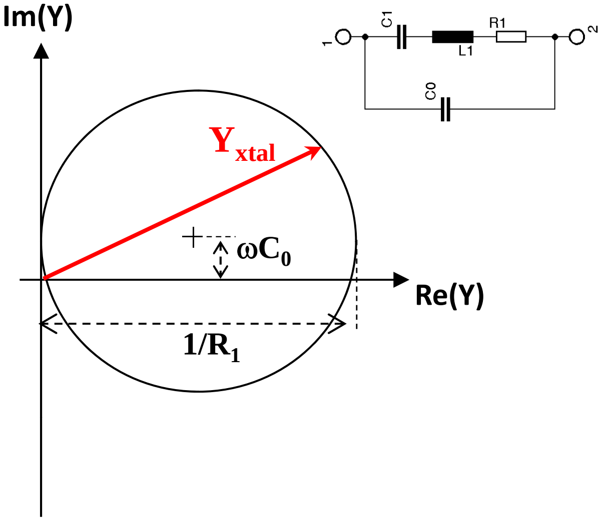
BVD with losses:
Locus of complex admittance Y = G+jB



Impedance Z_1(f)
of R_1, L_1, C_1

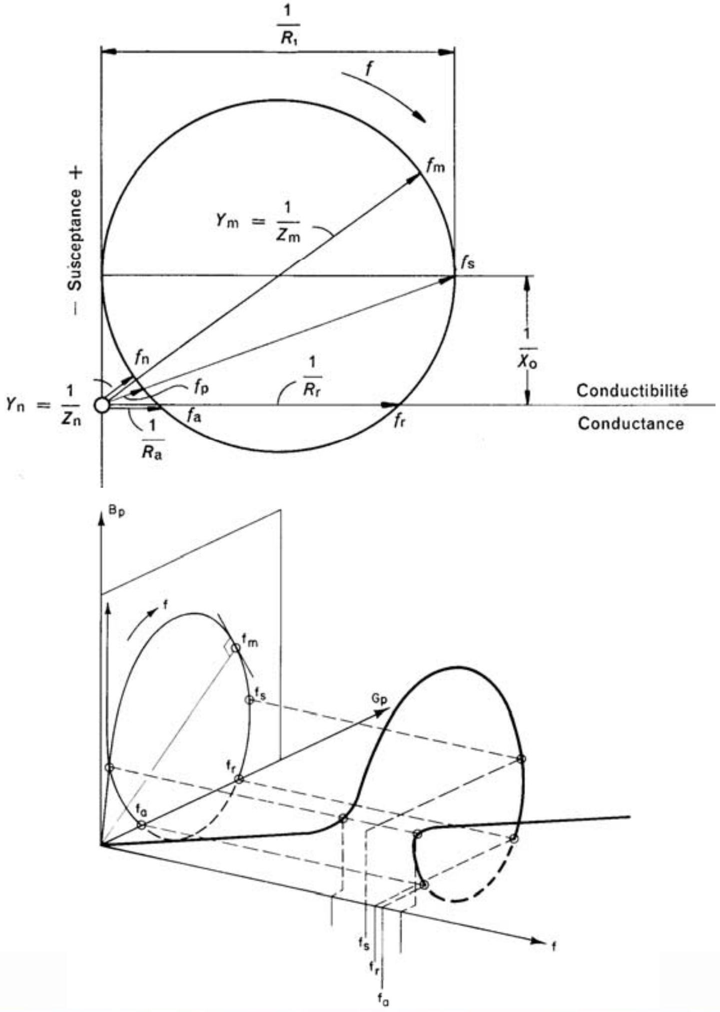


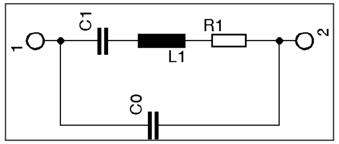
Admittance circle Y_1(f)
of R_1, L_1, C_1



Admittance circle Y_{BVD}(f)
of (R_1, L_1, C_1) || C_0

3D Presentation of admittance circle





Characteristic frequencies :

- Series resonance frequency f_s
- Resonance frequency f_r
- Minimum impedance-/ maximum admittance frequency f_m
- Parallel resonance frequency f_p
- Anti-resonance frequency f_a
- Maximum impedance-/ minimum admittance frequency f_n

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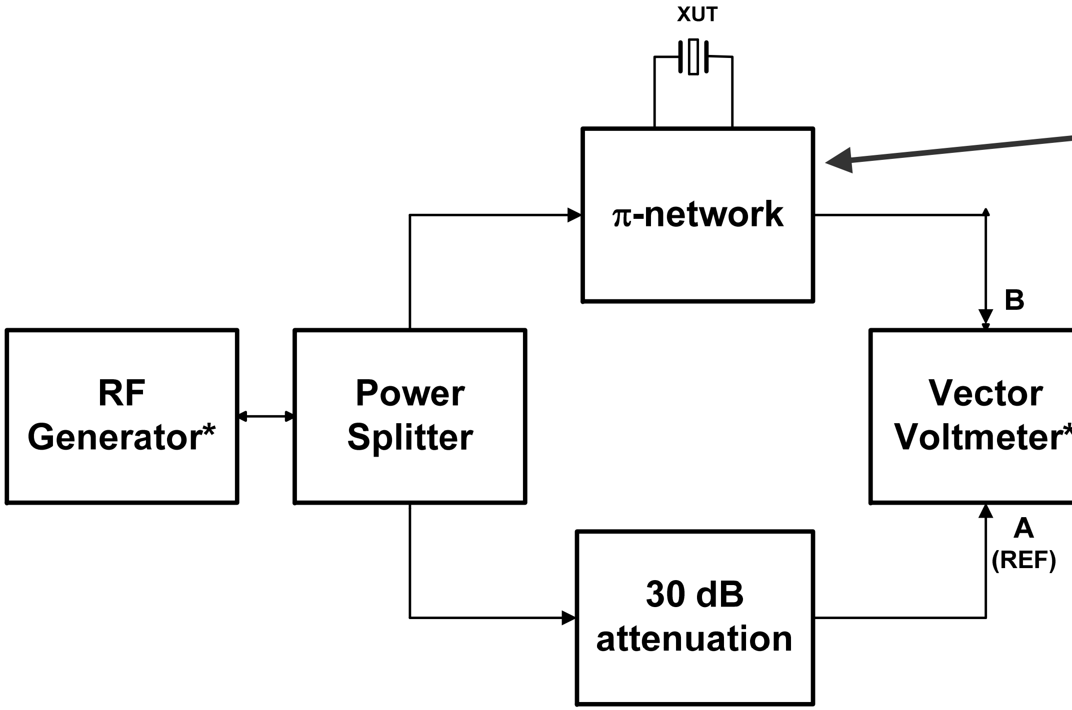
Traditional Measurement (IEC 60444-1+2) (up to 125 MHz)



XUT

π-network

B

RF Generator*

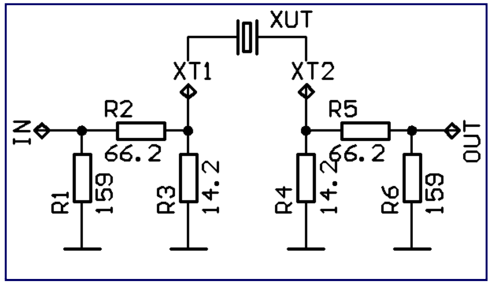
Power Splitter

Vector Voltmeter*

A (REF)

30 dB attenuation

π-network as in IEC 60444-1
(SMD: IEC 60444-8)



$R_{IN} = R_{OUT} = 50\ \Omega$

$R_{XT1} = R_{XT2} = 12.5\ \Omega$

$R_T = R_{XT1} + R_{XT2} = 25\ \Omega$

*RF Generator and Vector Voltmeter can be combined in a Network Analyzer

Measurement principle

- Calibration with short circuit (instead of XUT):
  - Set Phase φ_{AB} => 0
  - Set amplitude U_{BK} for proper crystal drive level
- Insert XUT and tune to zero phase near $U_{B\,max}$:
  - Frequency @ zero phase = resonance frequency f_r
  - Compute resonance resistance R_r from U_{B0} @ zero phase
  - Compute crystal current I_x from U_{B0}

$$R_r = \left(\frac{U_{BK}}{U_{B0}} - 1 \right) \cdot R_T$$

$$\frac{I_x}{mA} = \frac{U_{B0}/mV}{4{,}57}$$

- Compute L_1, C_1, Q from loaded bandwidth $\Delta f_{\pm 45°}$ und R_r

$$L_1 = \frac{(R_r + R_T)}{2\pi \cdot \Delta f_{\pm 45°}}$$

$$C_1 = \frac{\Delta f_{\pm 45°}}{2\pi \cdot f_r^2 (R_r + R_T)}$$

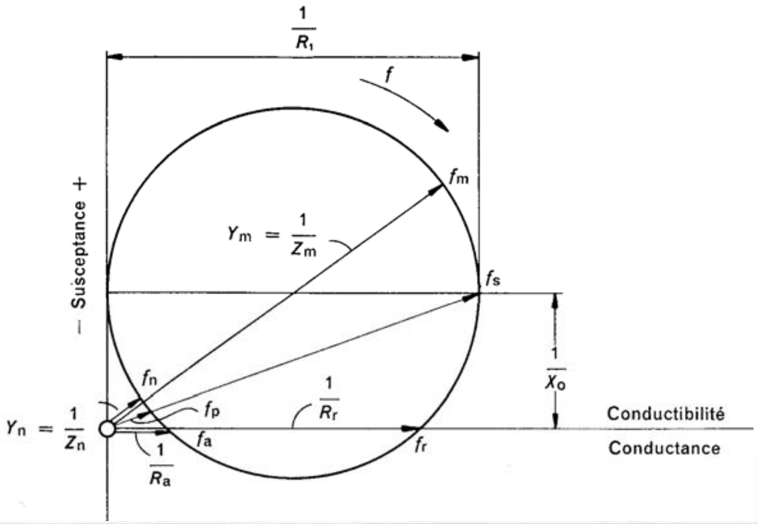
$$Q = \frac{\omega_r \cdot L_1}{R_r} = \frac{1}{\omega_r \cdot C_1 \cdot Rr}$$

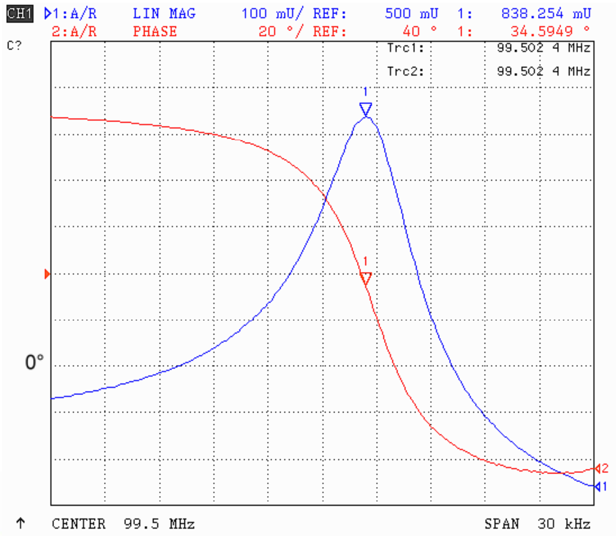
Note: Other phase offsets
than ±45° are possible

- Measure C_0 at 1 MHz:
  - with standard LCR meter or in π-network

Limitations at higher frequencies

- Traditional measurement neglects the impact of C_0, which is significant at higher frequencies:
  - The centre of the admittance circle moves up (from real axis)
  - At higher frequencies zero phase moves away from max. $|Y_x|$





Crystal
99.5 MHz
3rd OT

Limitations at higher frequencies

- Systematic error in the determination of frequency, resistance and the motional parameters increases
- Traditional method assumes an ideal π-network with
  - termination resistance $R_T = 25\ \Omega$ (real)
  - no cross-talk between the XUT ports
- Does not allow
  - to measure series resonance frequency f_s and R_1
  - to determine the effective shunt capacitance C_0' near nominal frequency
  - to determine the additional element values of the extended BVD circuits
- Does not make use of features of modern network analyzers

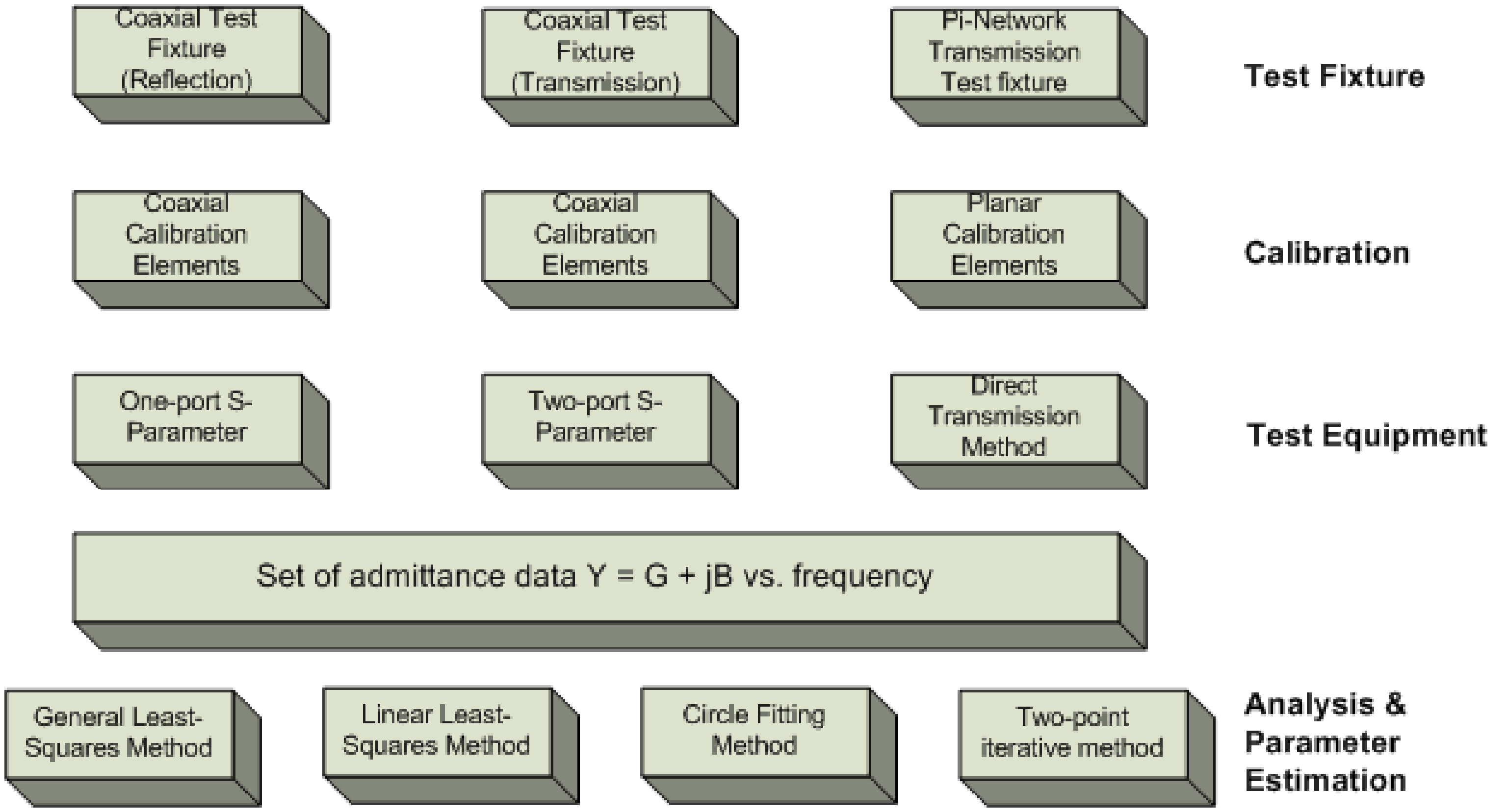
Error-Corrected Measurement Techniques of IEC 60444-5

- Full calibration using elements with known characteristic
  - „Through“ (short)
  - Calibration resistor (50 Ω or 25 Ω or other), and
  - „Open“
- Choice of Hardware realization
  - S-parameter test set
    - One-port reflection measurement of s_{11}
    - Two-port transmission measurement of s_{21} (and optionally s_{11} and s_{22})
  - Direct Transmission measurement of (voltage) amplitude and phase
  - Error correction allows a less stringent choice of the test fixture
    - Coaxial 50 Ω system, or
    - π-network (traditional), or
    - Modified transmission network
    - Precondition: availability of suitable, sufficiently accurate calibration elements

Error-Corrected Measurement Techniques of IEC 60444-5

- Computation of the complex crystal admittance in a frequency interval around the resonance
  - Calculation method depends on the used hardware version
    - conversion from s-parameters (namely s_{21}) to Y-parameters
    - from gain/phase data
- Computation of the parameters of the equivalent circuit from the admittance data set
  - Choice of different algorithms
    - Least-squares fit of admittance data to equivalent circuit elements
    - Least-squares fit of the admittance circle
    - Iterative 2-point method

Overview



Coaxial Test Fixture (Reflection)

Coaxial Test Fixture (Transmission)

Pi-Network Transmission Test fixture

Test Fixture

Coaxial Calibration Elements

Coaxial Calibration Elements

Planar Calibration Elements

Calibration

One-port S-Parameter

Two-port S-Parameter

Direct Transmission Method

Test Equipment

Set of admittance data Y = G + jB vs. frequency

General Least-Squares Method

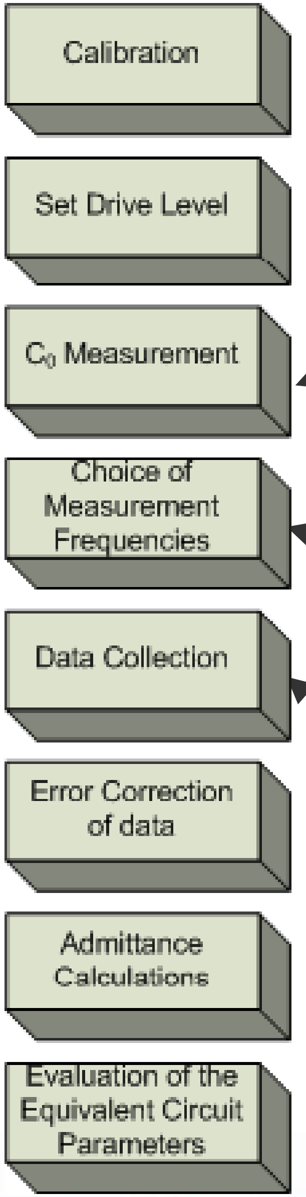
Linear Least-Squares Method

Circle Fitting Method

Two-point iterative method

Analysis & Parameter Estimation

Measurement Procedure



<u>f_s < 30 MHz:</u> measurement at 5 frequencies > 30 MHz,
e.g. 30.1 MHz, 30.2 MHz, … , 30.5 MHz
<u>f_s ≥ 30 MHz:</u> 3 pairs equidistant from f_s nom,
e.g. $f = f_s \cdot (1 \pm 0.05)$, $f_s \cdot (1 \pm 0.06)$, $f_s \cdot (1 \pm 0.07)$

<u>Least-square fitting and circle fitting methods:</u>
9…15 frequencies within $f_s \cdot (1 \pm 1/2Q)$
<u>2-point iterative method:</u>
(2+x), typ. 5 frequencies within $f_s \cdot (1 \pm 1/10Q)$,
iteratively approaching vicinity of f_s

CW mode, not swept measurement, because of
- inaccuracy of network analyzers
- settling time of crystal $t_r = 2.5 \ldots 3.5 \cdot Q_L/f$

After setting new frequency, wait for $t_d = t_{instr} + t_r$
with t_{instr} = settling time of analyzer

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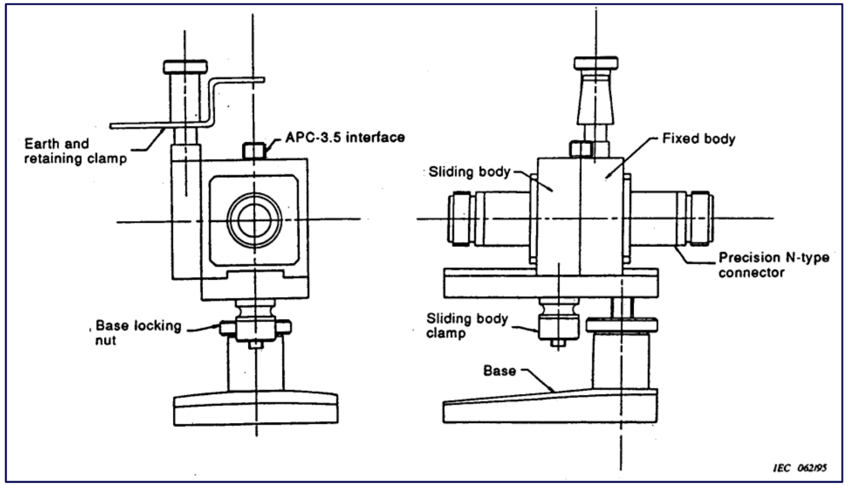
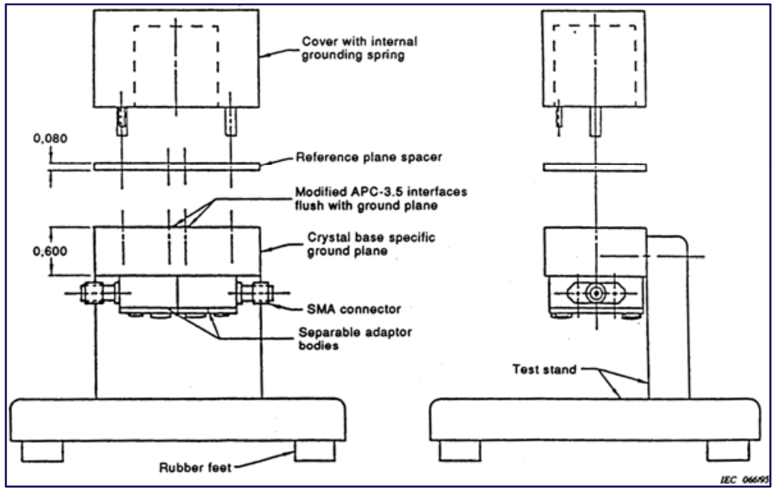
Proposed Test Fixtures

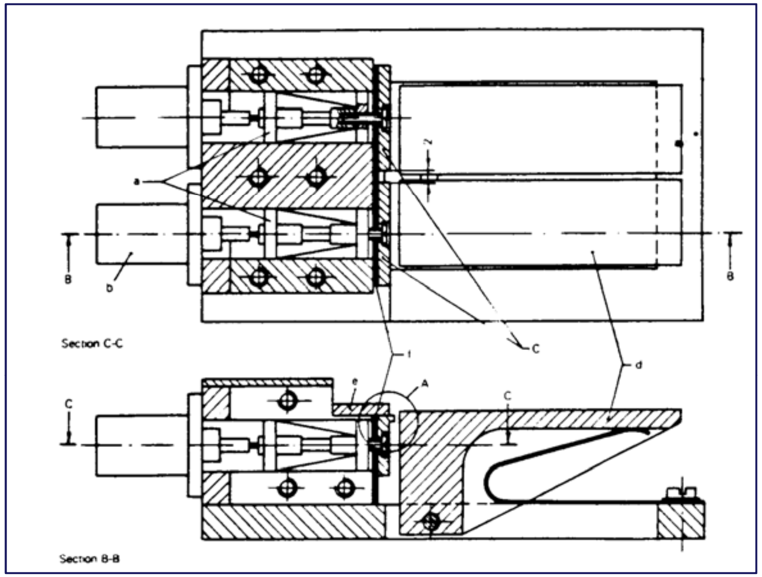
- S-Parameter Test
  - Coaxial reflection or transmission set based on APC3.5 or APC7
  - suited for leaded through-hole crystal units

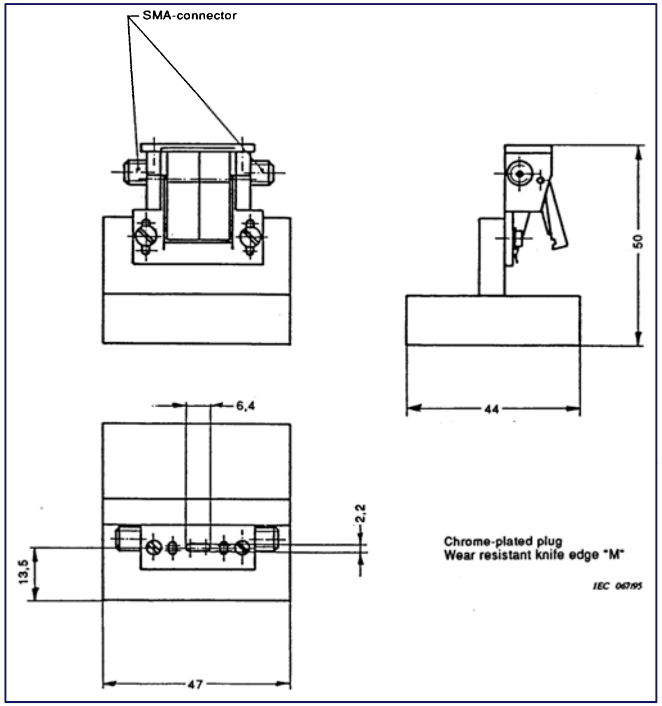




Proposed Test Fixtures

- Direct Transmission Test





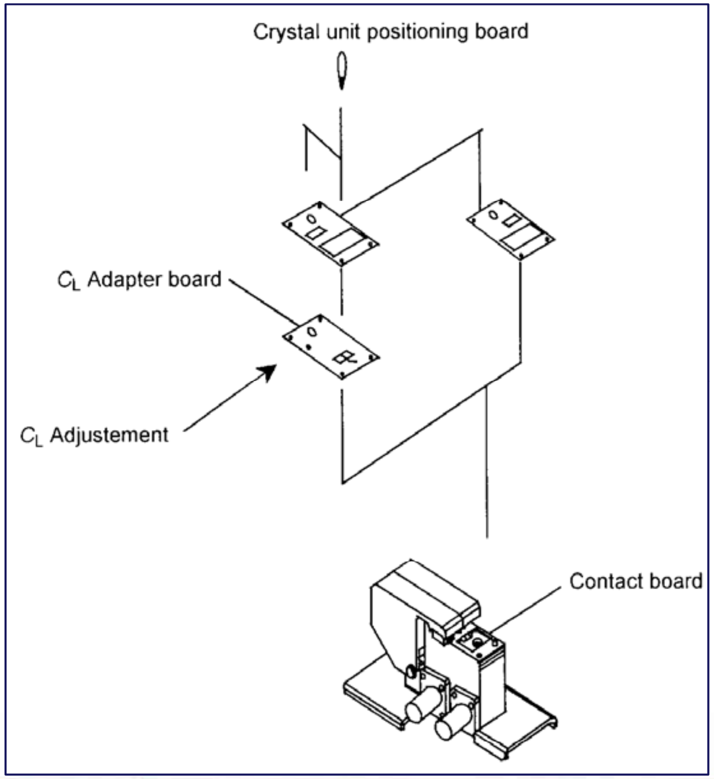
<u>Conventional coaxial π-network</u>

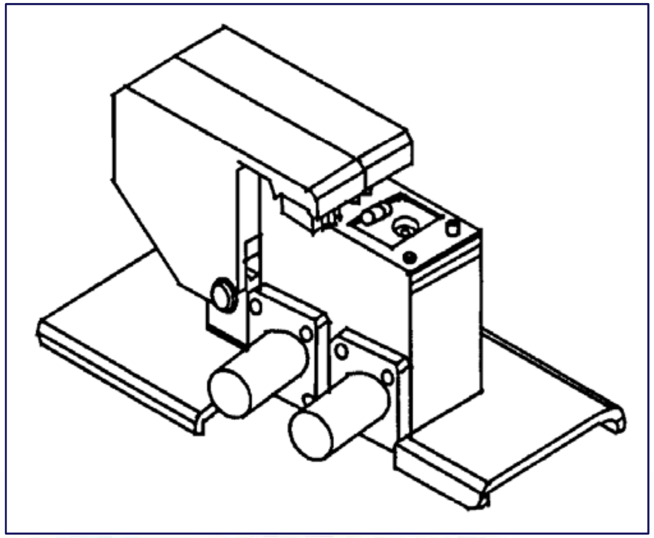
IEC 60444-1 (coaxial)

IEC 60444-5 (planar hybrid)

Proposed Test Fixtures

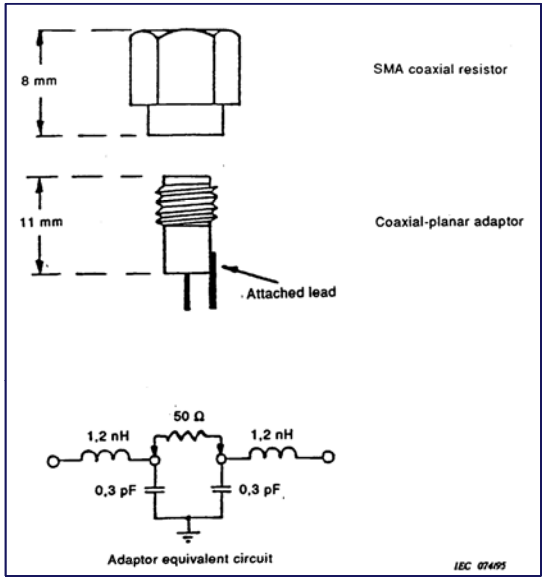
- Direct Transmission Test (SMD fixture IEC 60444-8)





Calibration Elements

- For S-parameter fixtures

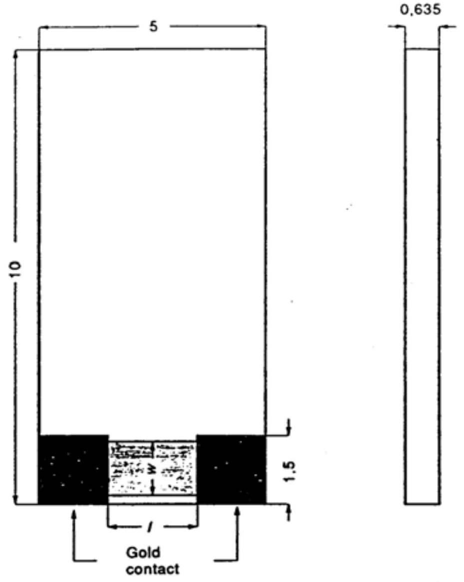


SMA (IEC 60444-5)

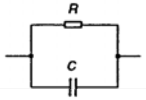
commercial APC3.5 calibration kit

Calibration Elements

- For π-networks



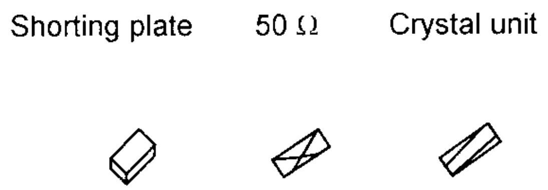
Calibration resistor (thin film)
Material: ceramics carrier Al_2O_3 coated



Equivalent circuit

IEC 073/95

Mechanical and electrical dimensions of calibration resistors			
R/ohm	l/mm	w/mm	C/pF
12,5	0,417	1,5	0,1
25	0,833	1,5	0,07
50	1,667	1,5	0,05
75	2,0	1,2	0,047
100	2,0	0,9	0,047



Through-hole THD (IEC60444-5)

SMD (IEC 60444-8)

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Error Corrections

- S-parameter
  - One-port (reflection) measurement

$$s_{11}^{A} = \frac{s_{11}^{M} - e_{00}}{e_{11} \cdot \left(s_{11}^{M} - e_{00}\right) + e_{01}}$$

with e_{ij} = error coefficients from calibration

  - Two-port (transmission) measurement
    - 12 term error model (e_{ij} and e_{ij}')
    - Transforms measured s_{ij}^{M} parameters to actual (corrected) s_{ij}^{A} Complex equations see Appendix A.2 of IEC 60444-5
  - Direct transmission measurement
    - Error correction performed with instrument calibration (see below)

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- Error Corrections
- **Algorithms for Parameter Evaluation**
- Discussion

Conversion of test data to admittance Y_x

- S-parameter measurements
  - Standard S-parameter to Y-parameter conversion

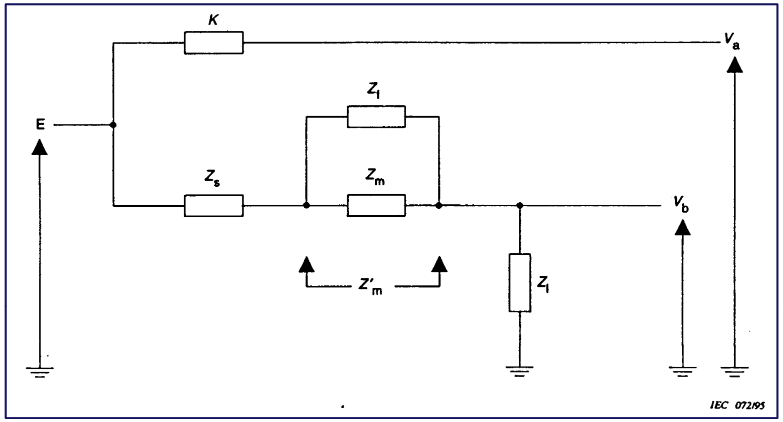
$$y_{11} = ((1-S_{11})\cdot(1+S_{22}) + S_{12}\cdot S_{21}) / D$$
$$y_{12} = -2\cdot S_{12} / D$$
$$y_{21} = -2\cdot S_{21} / D$$
$$y_{22} = ((1+S_{11})\cdot(1-S_{22}) + S_{12}\cdot S_{21}) / D$$

with $D = ((1+S_{11})\cdot(1+S_{22}) - S_{12}\cdot S_{21})$

  - Reflection
    Crystal admittance $Y_x = Y_{11}$
  - Transmission
    Crystal admittance $Y_x = Y_{21}$

Conversion of test data to admittance Y_x

- Direct transmission method
  - Computation of impedance from complex voltage ratios $v = V_B/V_A$ with V_A, V_B = output voltage (mag & phase) of A and B channel)
  - Calibration with “open”
    -> cross talk (mainly capacitance)
  - Calibration with “Short” and R_{cal}
    -> complex termination impedance R_T
  - Crystal impedance Z_x:



$$Z_x = (R_T + R_{cal})\frac{v_{cal}}{v_x} - R_T = R_T \cdot \left(\frac{v_{cal}}{v_x} - 1\right) + R_{cal} \cdot \frac{v_{cal}}{v_x}$$

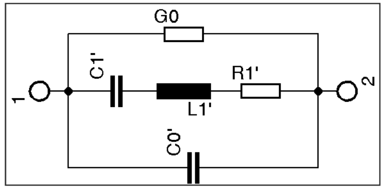
  - -> Crystal admittance $Y_x = 1/Z_x$

Conversion of Y_x to crystal parameters

- Least-squares fitting method
  - General LSQ fitting

    Minimize error function E

$$E = \sum_i W_i \cdot \left| Y_i - Y_i^M \right|^2$$



with W_i = weighting factors
Y_i = theoretical value of the admittance
Y_i^M = measured value of Y

$$Y_i = G_0 + \omega C_0 + \frac{1}{R_1 + j\omega L_1 + 1/(j\omega C_1)}$$

  - Linear LSQ fitting

    Uses the following approximations in the vicinity of resonance:

$$\omega C_0 \approx \omega_s C_0 = B_0$$

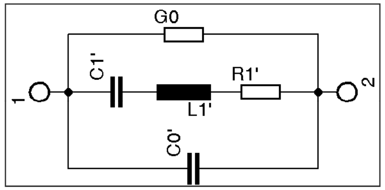
$$\omega L_1 - \frac{1}{\omega C_1} \approx 2(\omega - \omega_s) L_1$$

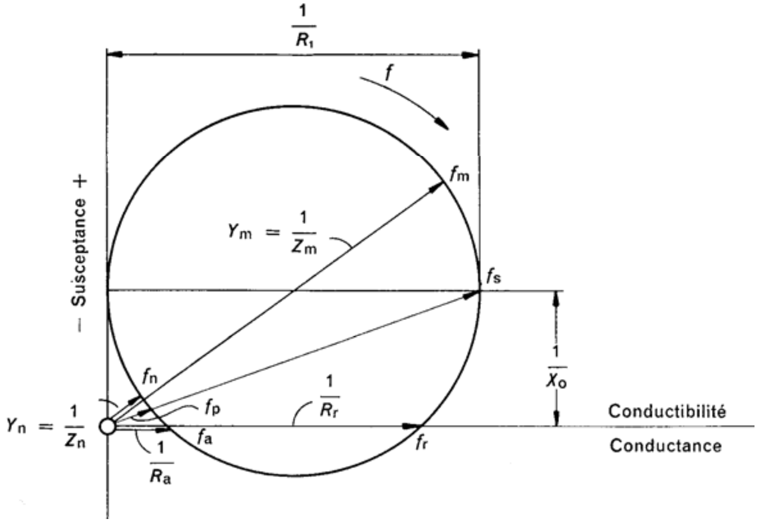
  - for more details refer to Clause 7.1 and 7.2 of IEC 60444-5

Conversion of Y_x to crystal parameters

- Circle-fitting method
  - In the vicinity of a resonance the admittance Y_x = G+jB can be described by the “circle” equation

$$\left(G - G_0 - \frac{1}{2R_1}\right)^2 + \left(B - B_0\right)^2 = \frac{1}{4R_1^2}$$



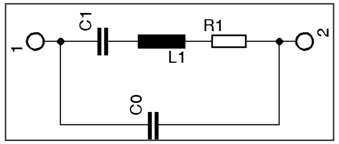


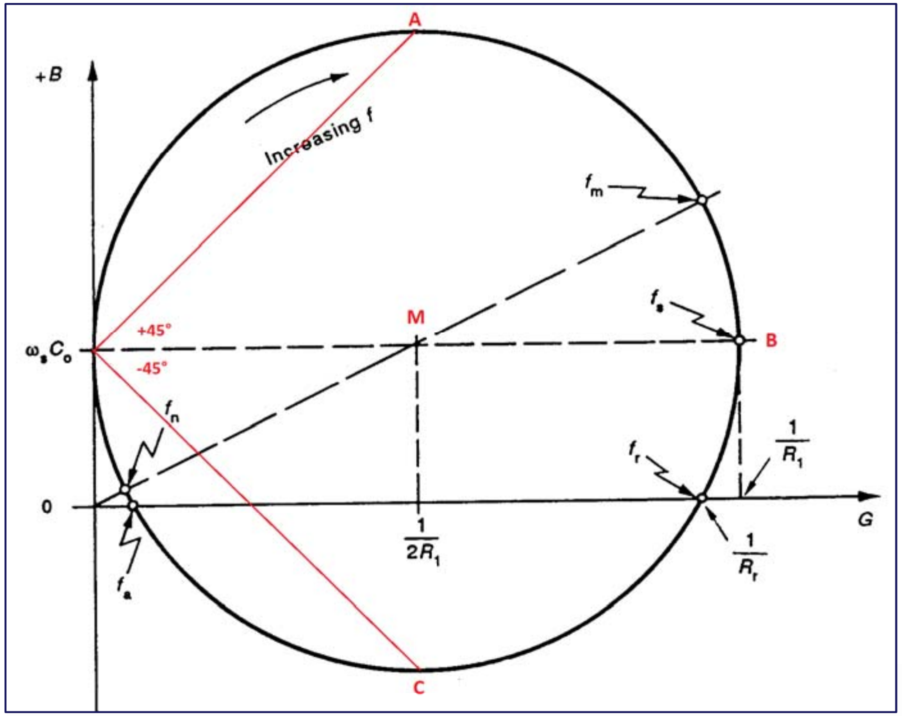
which describes a circle with a radius of $1/2R_1$, with the center at $[(G_0+1/2R_1), B0]$

  - The parameters R_1, $B_0=\omega C_0$ and G_0 are varied for a minimum least-squares error

Conversion of Y_x to crystal parameters

- Three-Point method (not in IEC 60444-5)
  - Search the three characteristic points A, B and C





A: max(Im(Y_x)) => f_s - 45°
B: max(Re(Y_x)) => f_s
C: min(Im(Y_x)) => f_s - 45°
M: (max(Im(Y_x))+min(Im(Y_x)))/2
-> Thus:

$$R_1 = \frac{1}{\max(\mathrm{Re}(Y_x))}$$

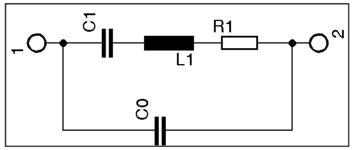
$$Q = \frac{f(B)}{f(C) - f(A)}$$

$$L_1 = Q\frac{R_1}{2\pi f_s}$$

$$C_1 = \frac{1}{2\pi f_s \cdot R_1 \cdot Q}$$

$$C_0 = \frac{\max(\mathrm{Im}(Y_x)) + \min(\mathrm{Im}(Y_x))}{2 \cdot 2\pi f_s}$$

Conversion of Y_x to crystal parameters



- Two-point iterative method
  - Basic idea:
    - BVD model contains 4 elements
    - Thus: Measurement of $\mathrm{Re}(Y_x)$ and $\mathrm{Im}(Y_x)$ at two frequencies ω_1 and ω_2 in the vicinity of the resonance allows an explicit solution for all four element values
    - However: The value of C_0 cannot be determined accurately enough from ω_1 and ω_2. It must be determined at one (or more) frequencies sufficiently apart from the resonance
  - With

$$Y(\omega_1) = a_1 + jb_1$$
$$Y(\omega 2) = a_2 + jb_2$$

and its complex conjugates

$$a_i^* + jb_i^* = \frac{1}{a_i + j(b_i - \omega C_0)}$$

the element values can be computed as follows:

$$L_1 = \frac{\omega_1 b_1^* - \omega_2 b_2^*}{\omega_1^2 - \omega_2^2}$$

$$C_1 = \frac{\omega_1^2 - \omega_2^2}{\omega_1^2 \omega_2 b_2^* - \omega_2^2 \omega_1 b_1^*}$$

$$R_1 = \frac{a_1^* + a_2^*}{2}$$

$$fs = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

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Pros and Cons

One-port S-parameter reflection method

Pros

- Good traceability because only coaxial calibration references are needed
- More sensitivity to low-R_1 crystals than two-port s-parameter method
- Greater measurement speed than two-port s-parameter method

Cons

- Not suitable for crystals with very high resistance
- Crystal under test is grounded at one terminal
- Electrode to case capacitances have to be measured independently
- Characterizes only 2-terminal devices
- Less accurate at low frequencies << 1 MHz
- Rather expensive test equipment

Pros and Cons

Two-port S-parameter transmission method

Pros

- Crystal is evaluated as a three-terminal device: more information available
- High-R_1 crystals are easily measured

Cons

- More complex calibration procedure
- Less sensitive to low-R_1 crystals
- Less accurate at low frequencies << 1 MHz
- Time-consuming test procedure, primarily for lab use
- Expensive test equipment

Pros and Cons

Direct Transmission method

Pros

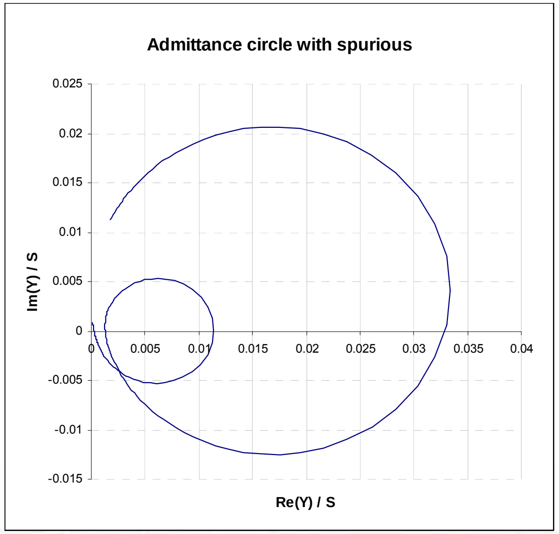
- Basic test equipment readily available
- High-R_1 crystals are easily measured
- Fast method, suitable for production
- Accurate at low frequencies < 1 MHz

Cons

- Less sensitive to low-R_1 crystals
- Calibration uses special non-coaxial reference impedances
- Electrode to case capacitances have to be measured independently, if the case is grounded. If floated, these are included in C_0

Limitations

- Drive Level Dependence (DLD) of the crystal unit
  - Low drive level (start-up)
  - Excessive drive level (crystal current)
  - Miniature and high frequency quartz crystal units are more sensitive to higher drive level (crystal current)
- Spurious responses close to the main resonance



Main resonance:
f_s = 100.000 MHz
$R_1 = 30\ \Omega$
C_1 = 0.5 fF
C_0 = 5 pF

Spurious mode:
f_s = 100.005MHz
$R_1 = 90\ \Omega$
C_1 = 0.15 fF

Issues

- Test fixture construction
  - Reference plane
  - Matching to 50 Ω coaxial environment
- Calibration elements
  - Must represent the calibration value at the reference plane
  - Must be characterized over a wide frequency range
  - “Primary” determination of the parameters of the calibration elements
  - Special problem for planar calibration elements (SMD)

  and last not least:

- Choice of appropriate equivalent circuit model
  - Which model is closest to the application?
  - Polarity of quartz crystal units?

Thank you for your kind attention