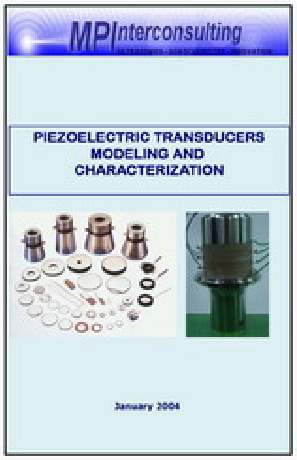


**BOOK:** **Piezoelectric Transducers Modeling and Characterization (complete technology and know-how inside).**

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# PIEZOELECTRIC TRANSDUCERS MODELING AND CHARACTERIZATION

# 1. Piezoelectric Converters Modeling and Characterization

Here are pictures of products that are related to modeling and characterization techniques presented in this paper. All of such devices and components can be measured, modeled and characterized using (more or les) the same methodology and the same terminology.

There are many possibilities to present and analyze equivalent models of piezoelectric converters. The analysis presented here will primarily cower modeling of high-power piezoelectric, Langevin, sandwich-converters (applicable in ultrasonic cleaning, plastic welding, sonochemistry and other power industrial applications), and the same analysis can easily be extended to cover much wider field of different piezoelectric transducers and sensors (but this was not the main objective of this paper). For electrical engineering needs (as for instance: when optimizing ultrasonic power supplies, in order to deliver maximal ultrasonic power to a mechanical load) we need sufficiently simple and practical (lumped parameter), equivalent models, expressed only using electrical (and easy measurable or quantifiable) parameters (like resistance, capacitances, inductances, voltages and currents). Of course, in such models we should (at least) qualitatively know which particular components are representing purely electrical nature of the converter, and which components are representing mechanical or acoustical nature of the converter, as well as to know how to represent mechanical load. For here described purpose, the best lumped parameter equivalent circuits that are fitting a typical piezoelectric-converter impedance (the couple of series and parallel resonance of an isolated vibration mode) are shown to be Butterworth-Van Dyke (**BVD**) and/or its electrical dual-circuit developed by Redwood (booth of them derived by simplifying the Mason equivalent circuit and/or making the best piezoelectric impedance modeling based on experimental results and electromechanical analogies). In this paper the two of mutually equivalent (above mentioned, **and later slightly modified**), dual electrical models will be used to present a piezoelectric converter operating in its series and/or parallel resonance, Fig. 1.

Above described objective has been extremely simplified after electronics industry developed Network Impedance (Gain-Phase) Analyzers (such as HP 4194A and similar instruments). Practically, for the purpose of modeling, it is necessary to select one single converter's operating mode (to select a frequency window which captures only the mode of interest, or the single couple of series and parallel resonance belonging to that mode) and let Impedance Analyzer to perform electrical impedance measurements by producing sweeping frequency signal in the selected frequency interval (and by measuring voltage and current passing on the converter connected to the input of Impedance Analyzer). The next step (implemented in Impedance Analyzers) is to compare the measured impedance parameters with theoretically known converter model (lumped parameters model, already programmed as an modeling option inside of Impedance Analyzer), and to calculate model parameters (practically performing the best curve fitting that places measured impedance values into theoretical impedance model). This way, in a few (button pressing) steps we are able to get numerical values of all (R, L, C) electrical components relevant (only) for selected converter mode and selected frequency range (and this is in most cases the most important for different engineering purposes, such as: optimizing ultrasonic power supplies, realizing optimal resonant frequency and output power control, optimizing converters quality…). We are also able to compare (using modern impedance analyzers) how close are measured impedance values (of a real converter), and values resulting from impedance curve fitting process. In cases of well-designed converters (and converters with sufficiently high mechanical quality factor) we are able to get almost 100% correct modeling in a selected frequency window (meaning that all measured and calculated R, L and C, lumped model parameters, are numerically almost 100% correct).

**The objectives of this paper are:**

1. To explain the most important (and simplified, practical and easy quantifiable), electrical lumped-parameters equivalent circuits, suitable to represent piezoelectric converter in its series and/or parallel resonance, for purposes such as converters characterization, qualification and optimization, for different electrical design purposes, as well as to explain qualitatively converter models regarding higher frequency harmonics, and

models when converter transforms mechanical input into electrical output (operating as a receiver or sensor).

2. To establish the very general concept of mechanical loading of piezoelectric converters (where mechanical load is presented in normalized form using the mechanical-load units comparable to internal resistance of the converter-driving electric circuit, or ultrasonic power supply).

3. To analyze the optimal power transfer of piezoelectric converters (when transforming electrical input into mechanical output), operating in series and parallel resonance, and to explain mechanical loading process and losses in both situations.

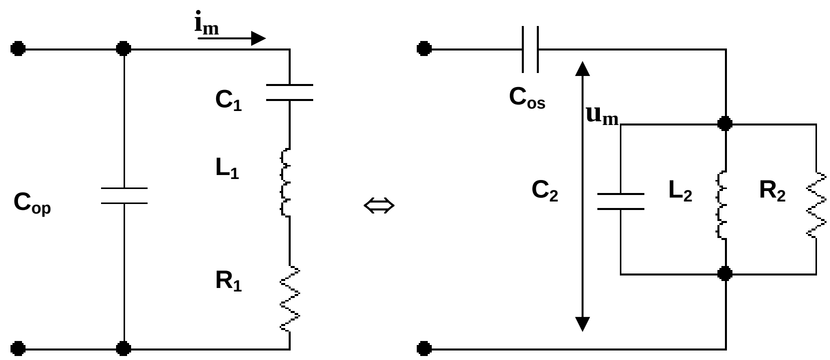



**Fig. 1 Piezoelectric Converter (One-Port), Dual, BVD Models valid in the close vicinity of an isolated couple of converters series and parallel resonances**

The Fig. 1 presents two of the most widely used lumped-parameters piezoelectric converter impedance models (mutually equivalent, **BVD** = **B**utterworth-**V**an **D**yke, dual-circuits models), valid for isolated couple of series and parallel resonances (of a non-loaded). In fact, on the fig Fig. 1 are presented the simplest models applicable for relatively high mechanical quality factor piezoelectric converters, where thermal dissipative elements in piezoceramics could be neglected. The more general models (again mutually equivalent), representing real piezoelectric (non-loaded) converters with dissipative dielectric losses and internal resistive electrode-elements (**$R_{op}$ (=) Leakage AC and DC resistance, $R_{os1} \approx R_{os2}$ (=) Dielectric resistive loss of piezoceramics**) in piezoceramics are presented on the Fig. 2. For high quality piezoceramics **$R_{op}$**, is in the range of 10 MΩ - 50 MΩ, and **$R_{os1}$**, **$R_{os2}$** are in the range between 50 Ω and 100 Ω, measured at 1 kHz, low signal (and can be calculated from piezoceramics **tan**δ value, or using HP 4194A, and similar Impedance Analyzers). In most of cases of high quality piezoceramics we can neglect **$R_{op}$** as too high resistance, and **$R_{os1}$**, **$R_{os2}$**, as too low values, but we should also know that dielectric and resistive losses are becoming several times higher when converter is driven high power, in series or parallel resonance, comparing them to low signal measurements.

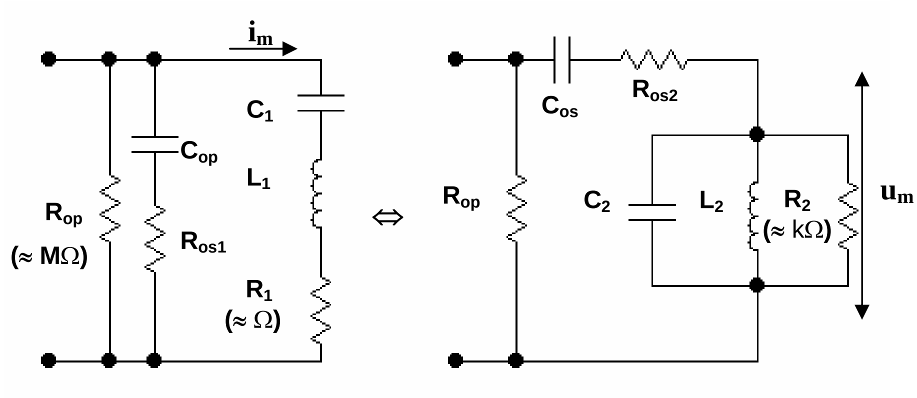



**Fig. 2 BVD Piezoelectric Converter Models with dissipative elements**

The other dissipative power losses (**$R_1$** and **$R_2$**) are belonging to the mechanical circuit branch and come from converter joint losses, from planar friction losses between piezoceramics and metal parts, from mounting elements and from material hysteresis-related losses (internal mechanical damping in all converter parts). The models from the Fig. 2 can be schematically simplified if we introduce abbreviated electric-elements symbolic presenting dissipative (real) inductances and capacitances together with their belonging resistances, using only one symbol, as for instance: For any electric combination (or connection) between one capacitance and one resistance we shall introduce the symbol **C***, and for any electric combination between one inductance and one resistance we shall introduce the symbol **L*** (since we can always find exact circuit transformations between two elements in serial and parallel connection). Doing this way, models presented on Fig. 2 will be simplified as given on the Fig. 3, and applicable circuit equivalents (used in Fig. 3) are presented on the Fig. 4.

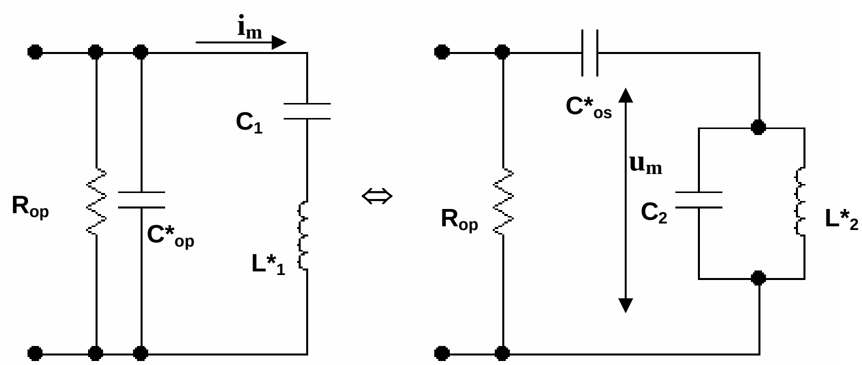
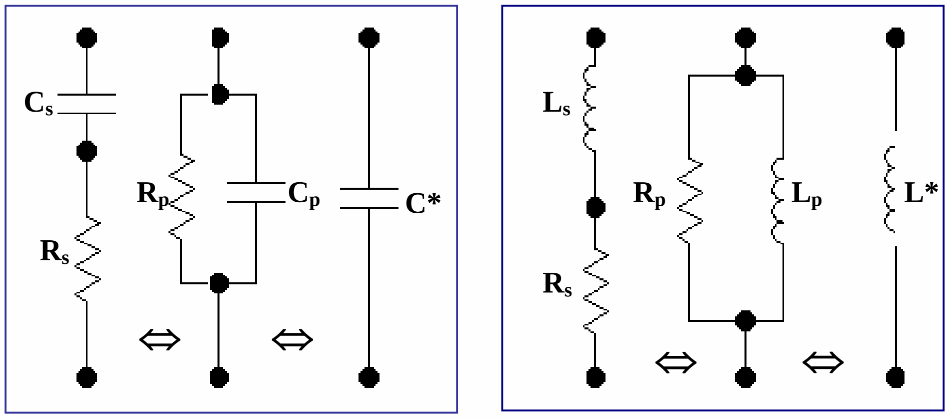



**Fig. 3 Simplified BVD Piezoelectric Converter Models**
**(L* and C* are presenting real inductances and capacitances with internally integrated, dissipative elements: Fully equivalent to models on Fig. 2)**




| | |
|---|---|
| $\mathbf{R_p = R_s(1+1/Q_s^{\,2}), R_s = R_p/(1+1/Q_p^{\,2})}$ | $\mathbf{R_p = R_s(1+Q_s^{\,2}), R_s = R_p/(1+Q_p^{\,2})}$ |
| $\mathbf{C_p = C_s/Q_s^{\,2}, C_s = C_p Q_p^{\,2},}$ | $\mathbf{L_p = L_s(1+1/Q_s^{\,2}), L_s = L_p/(1+1/Q_p^{\,2})}$ |
| $\mathbf{Q_s = \omega C_s R_s, Q_p = 1/\omega R_p C_p, \omega = 2\pi f}$ | $\mathbf{Q_s = \omega L_s/R_s, Q_p = R_p/\omega L_p, \omega = 2\pi f}$ |

**Fig. 4 Circuit Equivalents & Simplifications (explaining models from Fig. 3)**

The other elements on the Fig. 2 are: $\mathbf{C_{os} \approx C_{op}}$ **(=) Clamped, static capacitance/s of piezoceramics**, $\mathbf{C_{1/2}}$**,** $\mathbf{L_{1/2}}$ **(=) motional mass and stiffness elements of converter's mechanical oscillating circuit/s** (see Fig. 7 to find approximate mathematical relations between all model parameters)**.** We could also add in series to any of input converter terminals the cable (and winding) resistance, since every real converter has input electrodes, soldered or bonded (electrical) joints, and a cable (presently neglected parameters).

The influence of an external acoustic load on the converters' modeling is presented on the Fig. 5, by introducing loading resistances $\mathbf{R_{L1}}$ and $\mathbf{R_{L2}}$, as the closest and very much simplified equivalent of the real converter loading (in reality loading resistances $\mathbf{R_{L1}}$ and $\mathbf{R_{L2}}$, sometimes should be treated as complex impedances as the most general case).

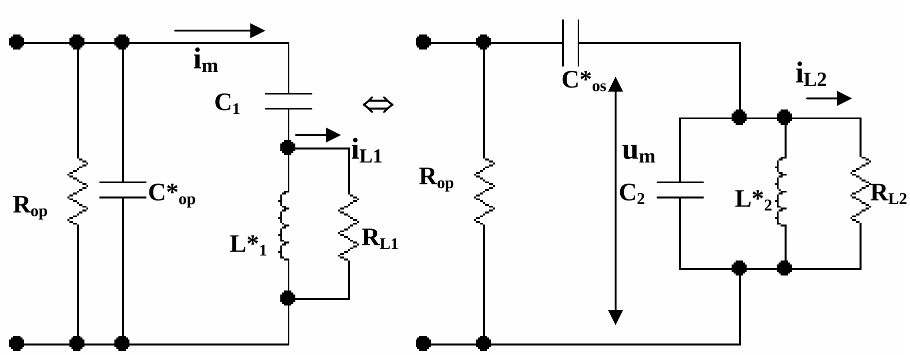



**Fig. 5 Alternative BVD Models of Loaded Piezoelectric Converters**

Based on equivalent electric circuits presented on Fig. 4, we can easily place parallel-loading resistances from Fig. 5 in series with inductances, just by calculating new equivalent frequency-dependant elements-values. In literature regarding the same problematic it is very usual to see that left-side piezoelectric converter-model from Fig. 5 has loading resistance in series with motional inductance and capacitance, and for the model on the right side of the Fig. 5 is usual that loading resistance is found in parallel with motional inductive and capacitive circuit elements (but using Electric Circuit Theory we can easily play with any of parallel or series elements combination, as presented on the Fig. 4). It is also clear that loading nature or load-resistance would change, depending how and where we place it (in situations, like in series connection/s with motional inductance, load resistance would increase with load-increase (starting from very low value), and in case of placing it in parallel with motional inductance (as presented on Fig. 5), load resistance would decrease with load-increase (starting from very high value)).

*In all above given converter models (Figs. 1,2,3,5), we can recognize motional current* $i_m$ *and motional voltage* $u_m$ *as the most important mechanical-output power/amplitude controlling parameters of piezoelectric converters in series and parallel resonance. When converter is operating in series resonance, in order to control its output power and/or amplitude we should control its motional current* $i_m$*, and in the regime of parallel resonance, output power and/or amplitude are directly proportional to the motional voltage* $u_m$*. More precisely,* ***<u>when we compare two operating regimes of the same converter, when converter is producing the same output power (in series and/or parallel resonance)</u>****, we can say that converter operating in series resonance is able to deliver to its load high output force (or high pressure) and relatively low velocity, and when operating in parallel resonance it is able to deliver high output velocity and relatively low force (knowing that output converter power is the product between velocity and force delivered on its front emitting surface). Here we are using the electromechanical analogy system:* ***(CURRENT ⇔ FORCE) & (VOLTAGE ⇔ VELOCITY)****. When we are talking about converter's series-resonance frequency zone, this is the case of motional* ***Current-Force*** *resonance (where converter's impedance has low values), and when we are talking about converter's parallel-resonance frequency zone, this is the case of motional* ***Voltage-Velocity*** *resonance (where converter has high impedance values). Automatically, if we realize by electrical means high motional current (current resonance, equal to series resonance), the converter will produce high motional force (it will operate in a force resonance). Also, if we realize by electrical means high motional voltage (voltage resonance, equal to parallel resonance), the converter will produce high motional velocity (it will operate in a velocity resonance). All above conclusions, for the time being, are based only on the analogy* ***(CURRENT ⇔ FORCE) & (VOLTAGE ⇔ VELOCITY)****, and later on, some more (experimental) supporting facts will be presented.*

It is also important to underline which circuit-elements (in all above found circuits, Figs. 1,2,3,5) are representing purely electrical elements of a piezoelectric converter, and which elements are only given as functional (and analog) electrical equivalents of converter's mechanical parts and its mechanical properties (including loading elements), see Fig.6.

It is very important to know that mechanical converter-loading, presented on Figs. 5 & 6, is equally and coincidently influencing changes, both in series and parallel converter impedance, basically reducing equivalent mechanical quality factor/s of a loaded converter (or coincidently increasing its series resonant-impedance and decreasing parallel resonant-impedance). ***This is the principal reason why (in this paper) an isolated couple of series and parallel resonances is treated as the same, single and unique oscillating-mode that can be driven in its current or voltage resonance, and produce force or velocity-dominant mechanical output. It is also shown to be possible to drive an ultrasonic converter high power, extremely efficiently, in any frequency (continuously) between its series and parallel resonance (when special converter reactive impedance-compensation is used).*** Since there is certain frequency shift between each couple of series and parallel resonances, and since most of today's converters (made by big players in ultrasonic industry worldwide) operate either in series or parallel resonance, in literature regarding converters modeling and converters measurements, many authors are talking about different vibration modes or different harmonics.