Power Converters and Control Schemes for Resonant Operated piezoelectric Actuators

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***Abstract* - Piezoelectric actuators, motors and transformers are becoming more and more important. Without exception the piezoelectric devices are fed by power electronic converters and at almost all applications they are operated in closed loop control. Considering the strong interdependence between actuator, power supply and control structure piezoelectric systems constitute typical mechatronic systems the components of which cannot be designed independently. The paper gives a classification of piezoelectric devices considering applications and operating modes suitable power converters and adapted control schemes.**

KEYWORDS

Piezoelectric actuators, resonant converters, control schemes.

I. INTRODUCTION

If a force is applied to an element of piezoelectric ceramics an electric field E will appear in the x_3-axis in which the element is polarized. Consequently a voltage u_P can be measured between electrodes which are mounted to the surfaces and electric charge will be present at the electrodes which means that mechanical energy has been converted to electrical energy due to the piezoelectric effect. For a long time this phenomenon has been used at sensors for measuring forces and pressures. The piezoelectric effect is reversible and can be used for electromechanical energy conversion, too.

During the last years piezoelectric actuators are becoming more and more attractive due to their high power density in particular when operated at high frequency and when making use of resonant amplification in the mechanical part. But not only electromechanical energy conversion is possible: Piezoelectric transformers can be easily realized by simply implementing two pairs of electrodes on the same piece of piezoelectric ceramics. Up to now piezoelectric actuators have been realized with low power only (motors less than 100 W, transformers less than 40 W), but high efforts are made to increase power ratings.

In contrast with conventional electromagnetic actuators piezoelectric devices do not make use of magnetic fields and do not behave inductive. In fact their capacitive behaviour has to be considered when designing the power supply. Furthermore the control of piezoelectric systems becomes a demanding task when resonant operation is aspired. Finally it turns out that the choice of the control structure for a piezoelectric system depends strongly on the type of power converter. Consequently a resonant operated piezoelectric system proves to be a typical mechatronic system the parts of which cannot be developed independently of each other.

In the following a survey will be given on piezoelectric actuators and motors, on adapted types of power converters and on control schemes which match the requirements of piezoelectric systems and the requirements being established by different applications. For general information on piezoelectric materials and devices see [1], [2].

II. Modelling of piezoelectric actuators

With regard to the inner behaviour of the piezoelectric device two operating conditions and correspondingly two types of applications can be distinguished.

Quasi-static operation of a piezoelectric system is present when the operating frequencies of the piezoelectric system is as low as necessary to ignore wave propagation inside the actuator and the associated mechanics. This is the case when the dimensions of the devices are small compared to the wave length λ which depends on velocity of sound v_S and operating frequency f by $\lambda = v_S/f$. To give an example: According to velocity of sound being 5,200 m/s for steel and 2,500 ... 4,600 m/s for piezoelectric ceramics wave length at a frequency of 20 kHz is 260 mm for steel and 125 ... 230 mm in piezo-ceramics. At quasi static operating conditions the piezoelectric device can be considered a lumped element.

On the other hand resonant operating conditions exist when the dimensions of the devices are not small compared to the wave length of operating frequency. In this case phenomenons of wave propagation must be considered.

II.A Basic equations of energy conversion

If a voltage u_P is applied to the electrodes of a piezoelectric element an electric field E is applied to the x_3-axis in which it is polarized and a deformation occurs in the x_3-axis (d33-effect) as well as in the perpendicular x_1-axis (d31-effect), see Fig. 1. From the permitted electric field strength of 2000 V/mm results the maximum change of dimensions which is less than 0,2 %. Therefore the piezoelectric actuators are well suited to achieve high forces at a small stroke but only a very small amount of energy is converted at each stroke.

The small amount of energy dw_i being converted electromechanically during a small movement of dx can be given by electrical or mechanical quantities

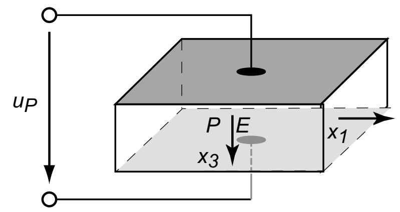

Fig. 1: Basic piezoelectric actuator

$$dw_i = f_i \cdot dx = u_i \cdot i_i \cdot dt \quad . \tag{1}$$

where f_i, u_i and i_i are an inner force, an inner voltage and an inner current, respectively. By introducing speed $v = dx/dt$ we get a similar expression for the inner power $p_i = dw_i/dt$

$$p_i = f_i \cdot v = u_i \cdot i_i \ . \tag{2}$$

From this equation two expressions can be derived

$$\text{a)} \quad \frac{f_{Pi}}{u_P} = \frac{i_{Pi}}{v} = A_P \qquad \text{b)} \quad \frac{f_{Mi}}{i_M} = \frac{u_{Mi}}{v} = K_M \tag{3}$$

where A_P is a constant in case of piezoelectric actuators while K_M is a constant in case of electromagnetic actuators e.g. a permanent excited dc motor. Thus, piezoelectric and electromagnetic magnetic actuators are reciprocal systems at which for instance the force depends either on an inner voltage or on an inner current:

In the following we will concentrate on the piezoelectric actuator. According to eq. 3 the inner mechanical and electrical quantities of these actuators are related by

$$f_{Pi} = A_p \cdot u_P \ , \qquad i_{Pi} = A_P \cdot v \tag{4}$$

II.B piezoelectric actuator at quasi-static operation

The inner current differs from the current being applied to the terminals because energy is stored in the electric field of a piezoelectric actuator and losses have to be considered which mainly depend on voltage. In the electrical part of the actuator these phenomenons are considered by a capacitance C_P and a resistance R_P, Fig. 2. For the terminal current we get

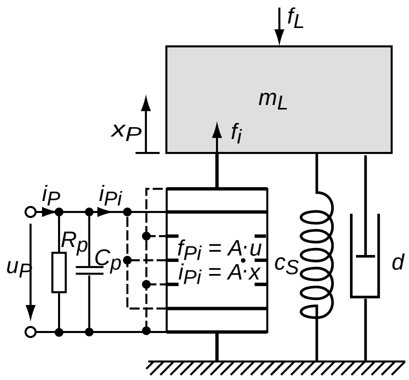

Fig. 2: Piezoelectric actuator loaded by prestress spring and load mass

$$i_P = C_p \cdot \frac{du_P}{dt} + \frac{1}{R_p} \cdot u_P + i_{Pi} \tag{5}$$

On the other hand the force f_L which is applied to the load differs from the generated force of the actor f_i because expansion of the actuator is hindered by the stiffness of the piezoceramic material and by the stiffness of a spring. which is used to prestress the piezoceramic device to avoid tensile strain, see Fig. 2. Thus, for the mechanical system we get

$$m_L \cdot \frac{d^2 x_P}{dt^2} = f_{Pi} - f_L - d_L \cdot \frac{dx_P}{dt} - c_S \cdot x_P \tag{6}$$

The quasi static behaviour of piezoelectric actuators and systems is described by eq. 4, eq. 5 and eq. 6 which can be represented by the block diagram shown at Fig. 3.

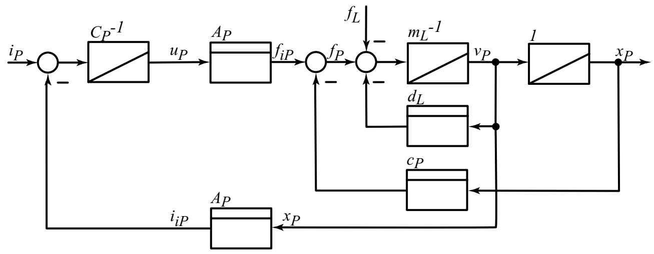

Fig. 3: Block diagram of piezoelectric actuator loaded by prestress spring and load mass

The system can also be visualizeded by an equivalent circuit which is derived when eq. 4 is used to substitute the mechanical quantities in eq. 6 by mechanical quantities. By this measure we get the differential equation of the mechanical part

$$\frac{m_L}{A_P^2} \cdot \frac{di_{Pi}}{dt} + \frac{d_L}{A_P^2} \cdot i_{Pi} + \frac{c_s}{A_P^2} \cdot \int i_{Pi} \ dt = u_P - \frac{1}{A_P} \cdot f_L \ , \tag{7}$$

which is the equation of a series resonant circuit

$$L_m \cdot \frac{di_{Pi}}{dt} + R_m \cdot i_{Pi} + C_m \cdot \int i_{Pi} \ dt = u_P - u_L \quad . \tag{8}$$

the parameters and variables of which are

$$\begin{aligned} &L_m = \frac{1}{A_P^2} \cdot m_L; \quad R_m = \frac{1}{A_P^2} \cdot d_L; \quad C_m = \frac{1}{A_P^2} \cdot c_S \\ &u_x = \frac{1}{A_P} \cdot f_x; \qquad i_{Pi} = A_P \cdot v \end{aligned} \tag{9}$$

The equivalent circuit of the whole system is shown at Fig. 4.

Note that the inner current i_{Pi} represents the speed of actuator and load

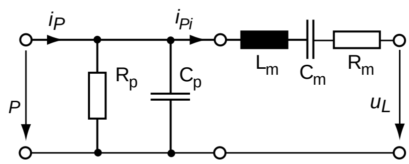

Fig. 4: Equivalent circuit of loaded piezoelectric actuator

while the voltages at the inductance L_m, the capacitance C_m and the resistance R_m represent the forces accelerating the mass, stressing the string and causing losses due to mechanical damping.

The output voltage u_L of the equivalent circuit represents the external force f_L applied to the oscillating system. If $f_L = 0$ the output of the circuit is shorted.

II.C Piezoelectric actuators at resonant operation

Because of the small deformation of the ceramics only a small amount of energy is converted at each stroke. Therefore most piezoelectric systems are operated at high frequencies in the ultrasonic range to increase the converted power. Due to high frequencies the elasticity and mass of the ceramics and of other mechanical devices cannot be neglected; even more, these are essential for the resonant operation of the actuators which make use of structural oscillations.

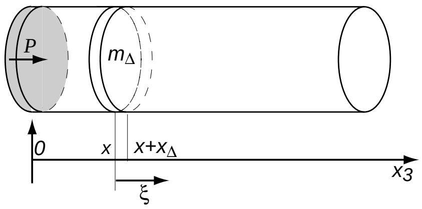

Fig. 5: Definition of coordinates

The mechanism of structural oscillations is explained at a passive steel bar in which a plain wave is induced by a thin piezoelectric actuator at $x = 0$. The waves propagate in x_3-axis, see Fig. 5. To derive the wave equation a thin slice of thickness x_Δ and mass m_Δ is considered. Calculation of its deviation ξ from the initial position x and its compression dx_Δ and strain σ results in the wave equations

$$\frac{d^2\xi}{dt^2} = v_S^2 \cdot \frac{d^2\xi}{dx^2} \quad \text{and} \quad \sigma = -E \cdot \frac{d\xi}{dx} \tag{10}$$

where the velocity of sound $v_S = \sqrt{E/\rho}$ is determined by the modulus of elasticity E and the density ρ of the material.

Solving the wave equation results in

$$\begin{aligned} \xi(x,t) &= (A \cdot \cos(2\pi f \cdot t) + B \cdot \sin(2\pi f \cdot t)) \cdot \\ &\quad \cdot (C \cdot \cos(2\pi \cdot x/\lambda) + D \cdot \sin(2\pi \cdot x/\lambda)) \\ \sigma(x,t) &= -\frac{2\pi \cdot E}{\lambda} \cdot (A \cdot \cos(2\pi f \cdot t) + B \cdot \sin(2\pi f \cdot t)) \cdot \\ &\quad \cdot (D \cdot \cos(2\pi \cdot x/\lambda) - C \cdot \sin(2\pi \cdot x/\lambda)) \end{aligned} \tag{11}$$

The constants of integration have to be calculated from the boundary conditions: $\xi(0,t) = 0$, $\sigma(L,t) = 0$. The last equation is satisfied for an infinite number of discrete resonance frequencies which are in accordance with

$$\lambda_k = \frac{1}{2k+1} \cdot 4L \qquad f_k = \frac{v_S}{\lambda} = (2k+1) \cdot \frac{v_S}{4L} \qquad \text{where } k = 1, 2, 3, \ldots \tag{12}$$

An example of practical importance is given at Fig. 5. The bar shown here is excited and fixed at $x = L/4$ (therefore $\xi(L/4, t) = 0$) with a frequency for which $\lambda = L$ holds. At both surfaces of the bar no force and no strain are present ($\sigma(0,t) = 0 = (L,t)$). Due to these boundary conditions of the this system resonance is possible for

$$L/4 = k \cdot \lambda_k/4 \qquad \lambda_k = L/k \qquad f_k = k \cdot v_S/L \qquad \text{where } k = 1, 2, 3, \ldots \tag{13}$$

Due to an infinite number of discrete wave lengths (characterized by order k) an infinite number of associated resonance frequencies f_k exists. In accordance with this fact the equivalent circuit of the resonant operated actuator has to be extended by an infinite number of resonant circuits, see Fig. 6.

The output voltage u_L of the circuit represents the external force f_L which is applied to the surface of the actuator.

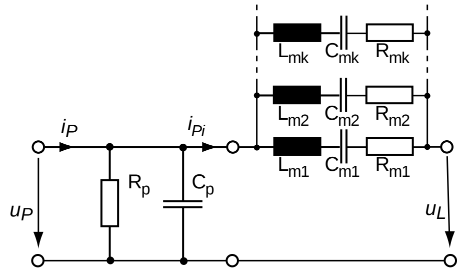

Fig. 6: Equivalent circuit of resonant operated actuator

At Fig. 7 no forces are applied to both surfaces of a sonotrode and the actuator is placed at $x = L/4$. Hence $\sigma(0,t) = \sigma(L,t) = 0$ hold and the support of the bar will not be stressed as far as $\xi(L/4, t) = 0$ is satisfied. So we get

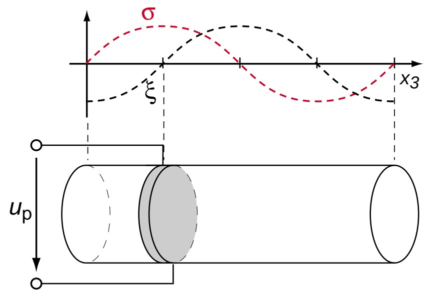

Fig. 7: Resonant operated sonotrode

$$L/4 = (2k-1) \cdot \lambda_k/4 \qquad f_k = (2k-1) \cdot v_S/L \tag{14}$$

For transfer of power to a load that is coupled to the bar's surface strain as well as deviation must be present at the positions of the actuator ($x = L/4$) and of the surface (e.g. at $\lambda = L$). These requirements can be fulfilled by a variation of frequency and wave length.

Finally the deviation appearing of the surface at $x = L$ can be increased by reducing the bar's cross-sectional area. As shown in Fig. 8 reduction is applied at $x = 3L/4$ where no deviation takes place. Since the longitudinal force f must be equal on both sides of the cross-sectional reduction

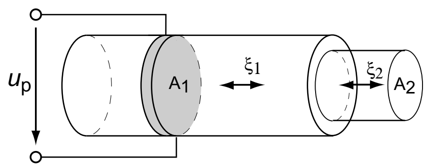

Fig. 8: Sonotrode with cross-sectional reduction

$$\frac{\hat{\sigma}_2}{\hat{\sigma}_1} = \frac{A_1}{A_2} \quad \text{and} \quad \frac{\hat{\varepsilon}_2}{\hat{\varepsilon}_1} = \frac{\hat{\xi}_2}{\hat{\xi}_1} = \frac{A_1}{A_2} \tag{15}$$

must hold for the amplitudes of strain $\hat{\sigma}$, compression $\hat{\varepsilon}$ and deviation $\hat{\xi}$. Note that in practice the cross-sectional reduction must not be introduced as abrupt as in Fig. 8 to avoid destruction by notch effect.

In practice sonotrodes are normally equipped with stack actuators consisting of thin ceramic slices which are alternatingly polar-

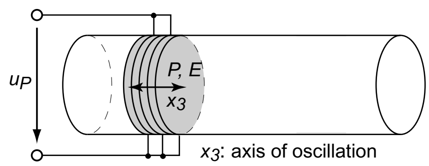

Fig. 9: Sonotrode with stack actuator

ized and are separated by electrodes according to Fig. 9. By this measure very high voltages can be avoided which would be required to activate monolithic actuators of great thickness. For the design of stack actuators odd numbers of slices are preferred because in this case both electrodes being in contact with the oscillating steel bar can be grounded.

For the discussion of suitable power converters and control schemes the model of piezoelectric actuator can be simplified as follows: First, resistance R_p can be neglected due to small and unimportant piezoelectric losses. Second, only one series resonant circuit of Fig. 6 needs to be considered as far as the input voltage is sinusoidal and only one resonant mode is excited. Last not least, the load being applied to the actuator can be approximately modelled by a linear impedance which is connected to the output of the equivalent circuit. Equivalent inductance L_L, capacitance C_L and resistance R_L of the load can be combined with the accordant devices of the actuator L_m, C_m, R_m. Resulting parameters are

$$L_M = L_m + L_L \qquad C_M = \frac{C_m C_L}{C_m + C_L} \qquad R_M = R_m + R_L \quad (16)$$

Finally we get the equivalent circuit shown at Fig. 10a) which is reduced to that of Fig. 10b) at resonance.

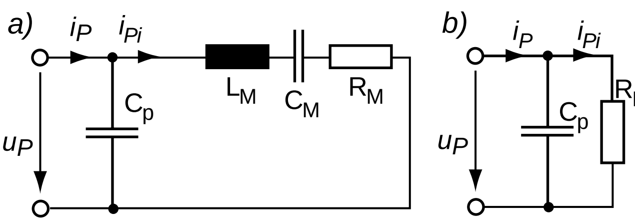

Fig. 10: Approximate equivalent circuits of loaded actuator
a) in surrounding of resonance frequency,
b) exactly at resonance frequency

III. Applications of resonant operated actuators

III.A Sonotrodes for ultrasonic machining

Processing of materials can be accelerated and wear of the tool can be reduced when an ultrasonic oscillation is superimposed in quadratur to the cutting speed of the tool. For this purpose sonotrodes (ultrasonic power converters) are used consisting of a steel bar which is operated in structural resonance by a piezoelectric actuator, see Fig. 11. Normally resonance frequency is in the range

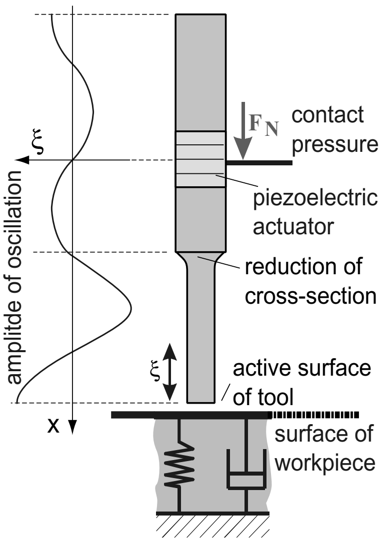

Fig. 11: Sonotrode

of 20...30 kHz and reduction of cross-section is used to increase the amplitude of oscillation at the active surface.

The surface of the bar can be equipped with any machining tool like drill, knife, cutting chisel, dental elevator or bonding tool at production of chips. At other applications ultrasonic is applied to a liquid in which objects are cleaned or to a gas in which drops of liquid are spattered.

For excitation of sonotrodes only small volumes of piezoelectric material is required. Sonotrodes therefore own good power factors (0.75 ... 0.9 at mechanical resonance).

III.B Piezoelectric transformers

A piezoelectric transformer using d_{33}-effect comes into being when a second actuator is introduced into the system as shown at Fig. 12a). Normally all the oscillating bar is from piezoelectric material (no steel) and different shapes are possible.

The transmission ratio of the transformer is determined by the design of the piezoelectric actuators. The system is operated at $\lambda = L$ as shown by the dotted lines of Fig. 12b). Excellent isolation of primary and secondary is achieved if the whole bar is made from ceramics and no steel is used.

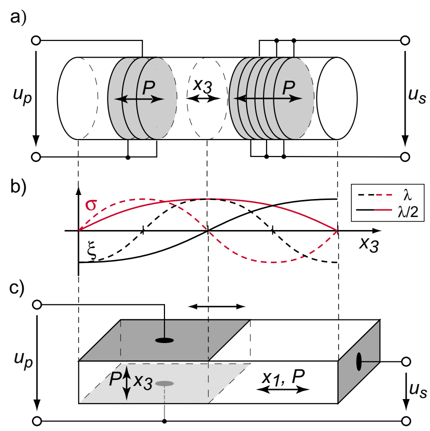

Fig. 12: Piezoelectric transformers
a) using d_{33}-effect
c) using d_{31}-effect
b) distribution of strain and deviation

The transformer proposed by Rosen in 1958 [3] is shown at Fig. 12c). Polarisation of the piezo-ceramic device is in the x_3-axis in the left half and in the horizontal x_1-axis in the right half. Due to the oscillation which is excited by the left-side input actor in the vertical x_3-axis an oscillation appears in the horizontal x_1-axis, too, causing an electrical field of same direction in the right half. Since inserting an electrode in the middle of the ceramics causes problems one of the primary electrodes is used for the secondary, too. Hence the unit behaves like an autotransformer.

Piezo-transformers can also be designed by using ring-shaped ceramics which can oscillate in radial, axial or tangential direction. They offer small size and good efficiency and have been realized e.g. for 10 W for power supply of handys [4].

III.C Ultrasonic travelling wave motors

At the well-known ultrasonic travelling wave motor a piezoelectric ring-shaped actuator system excites a travelling bending wave at the circumference of a circular brass disc [5], see Fig. 13a). The actuator system consists of a piezoceramic ring which is divided into two actuator phases and two small sensor sections. By means of expanding and contracting zones each actuator phase generates a standing wave at 40...45 kHz which superimpose to a travelling wave, see Fig. 13b). The sensors are used to measure and to control the spacial amplitudes of the standing waves. $\Omega = \omega / \omega_{r1}$

For power take-off a rotor-ring is pressed to the circumference of the stator-disk where the travelling wave causes a rotary movement of the rotor. Torque is generated in a difficult way by friction which causes a poor efficiency (less than 50 %). Since a great volume of piezo-ceramics is required to initiate the travelling wave power factors at mechanical resonance ω_{r1} are less than 0.1, i.e. $\omega_{r1} C_P > 10 / R_M$. Travelling wave motors with rated power up to 100 W generate high torque at low speed and are in use for autofocus in cameras and in cars for adjustment of head-rests and steering wheels [6].

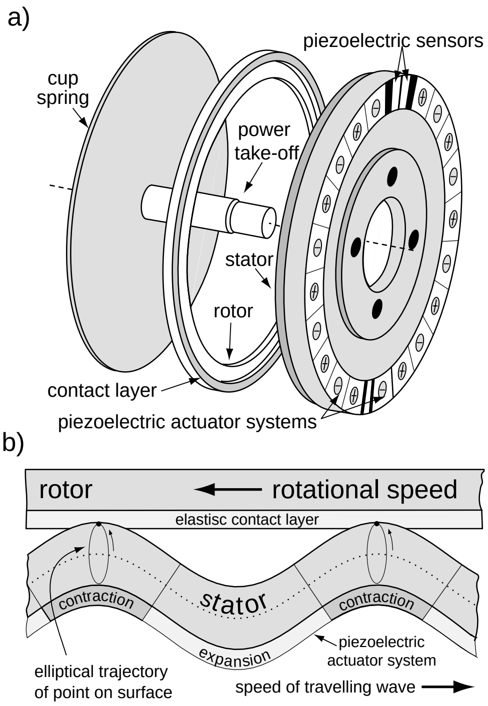

Fig. 13: Ultrasonic travelling wave motor
a) exploded view
b) generation of travelling wave

IV. POWER CONVERTERS AND CONTROL

To transfer the net power to the mechanical output with minimum stress of the mechanical part piezoelectric actuators should be operated as close as possible to a resonance frequency. This means that one mode of oscillation (order k) has to be chosen; normally the lowest order ($k = 1$) is used. As a result fundamental frequency of the power converter is determined by the resonance frequency of the mechanical system. Furthermore sinusoidal input voltage and current have to be delivered by the converter and consequently equivalent circuits of Fig. 10a) can be used to model piezoelectric actuators for design of power converters and control schemes.

The frequency characteristic of the input admittance of this equivalent circuit is shown at Fig. 14. Due to three reactive devices two resonance frequencies are existing.

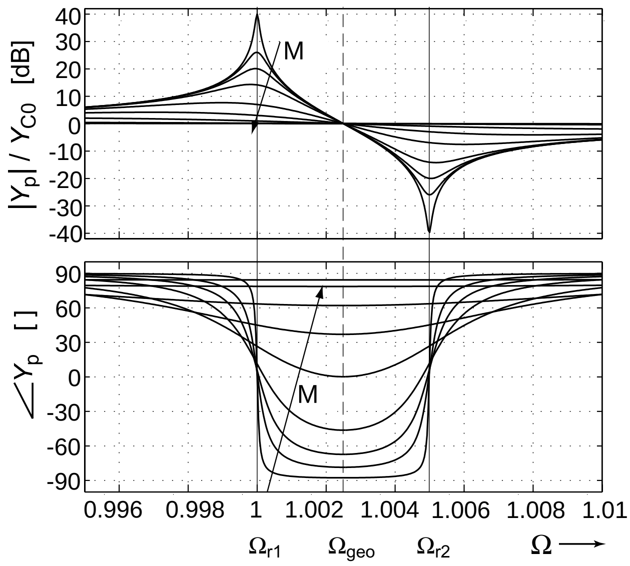

Fig. 14: Frequency characteristic of actuator systems' input admittance (normalised frequency: $\Omega = \omega / \omega_{r1}$)
M = .001; .05; .01; .5; 1; 2; 5; 10 where $M = \omega_{r1} C_P R_M$

$$\omega_{r1} = \frac{1}{\sqrt{L_M C_M}} \qquad \omega_{r2} = \frac{1}{\sqrt{L_M \frac{C_M C_P}{C_{MP} + C_P}}}. \qquad (17)$$

Series resonance (ω_{r1}) is determined only by the mechanical part of the system. At this resonance input impedance of the equivalent circuit is low which means that low input voltage and high input current i_{Pi} are required to deliver the power demanded by resistor R_M representing load and losses.

Parallel resonance (ω_{r2}) depends additionally on the capacitance of the piezo-ceramics. In contrast with series resonance high input voltage and low input current are required. Note that ω_{r2} is always higher than ω_{r1}. With regard to high voltage levels required by piezoelectric actuators operation at series resonance is normally preferred.

In case the system is operated exactly at series resonance the input admittance of the actuator can be seen from Fig. 10b),

$$Y(j\omega = j\omega_{r1}) = R_M^{-1} + j\omega_{r1} C_P \qquad (18)$$

When the system is investigated in detail the ratio of the reactive and the active part $M = \omega_{r1} C_P R_M$ proves to be an important parameter by which two classes of systems can be distinguished [11]: Admittance ratio M indicates whether the input behaviour of the system is determined by the mechanical resonant part or by the piezoelectric capacity of the actuator.

If $M = \omega_{r1} C_P R_M < 1/2$ holds two frequencies exist at which the imaginary part of the input admittance disappears and $\angle G_{LC} = 0$ holds, see Fig. 14. As a result no reactive power is required by the actuator when operated at one of these frequencies. Condition $M < 1/2$ normally exists at sonotrodes where the actuator itself forms the oscillating structure.

In contrast at systems with $M = \omega_{r1} C_P R_M > 1/2$ the input admittance has a capacitive imaginary part at all frequencies. This is the case with ultrasonic travelling wave motors. At these motors a rather great volume of piezoceramics is required to excite oscillation of the stator disc and causes a great piezoelectric capacitance. Consequently these motors always have a high demand for reactive power.

V. POWER CONVERTERS AND CONTROL SCHEMES FOR piezoelectric ACTUATORS [11]

Power supplies for piezoelectric actuators normally are DC link converters, see Fig. 15.

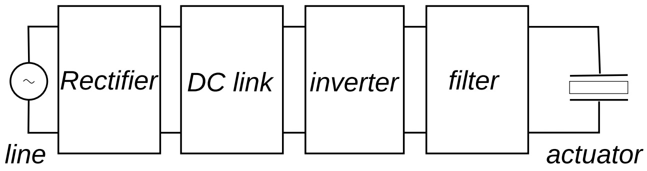

Fig. 15: Stages of DC link converter

Between the actuator and the inverter a filter with at least a series inductor must be inserted to decouple the capacitance of the actuator from the voltage source inverter.

For realisation of the inverter stage half bridge and full bridge as well as push-pull converter can be used, see Fig. 16. For the design of the filters and the operation of the inverter stage two basic possibilities are existing.

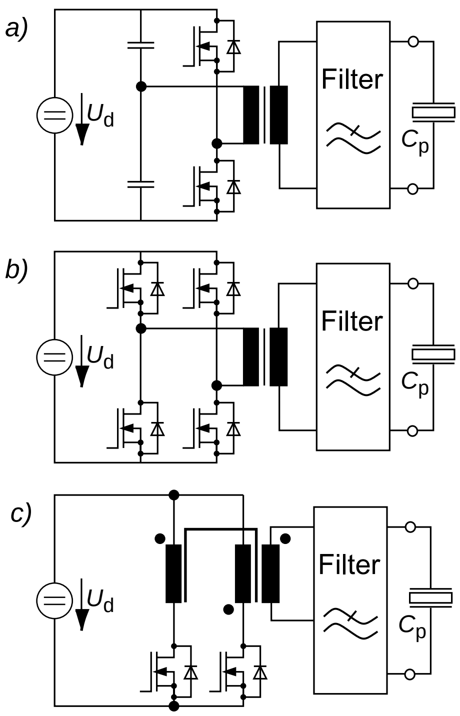

Fig. 16: Inverter stages

Furthermore attention must be paid to the low order harmonics of the fundamental frequency because these may excite unwanted oscillation modes which impair proper operation of the system.

Last not least in most cases the output must be separated from the input by a transformer. In many cases this device is inserted between the inverter and the piezoelectric actuator and therefore has to be designed in accordance with the transmitted apparent power.

As already mentioned two basic alternatives for the design of the filter exist which results in different features of the system.

V.A PWM converters

As is generally known low order harmonics can be avoided by operating the inverter at high switching frequencies at which low current ripple can be achieved with small filter inductors [8]. By use of a suitable control structure in combination with PWM sinusoidal input current can be applied to the actuator causing voltage also to be sinusoidal.

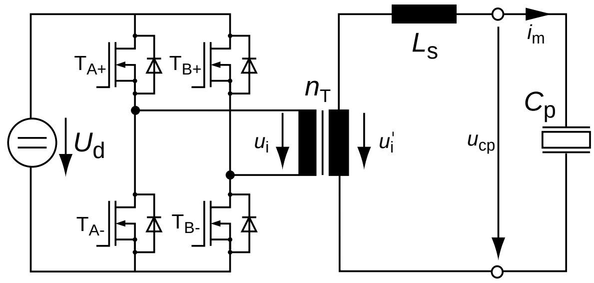

Fig. 17: Full bridge inverter with PWM filter inductor

The frequency characteristics resulting from the actuators capacitance and the small series inductor shows a resonance appearing at a frequency far beyond the operating frequency fs, see Fig. 18. Due to this fact parameter variations of the resonant circuit hardly influence the output voltage of the filter. Such variations can be caused by the actuator's capacitance which depends on temperature or by the load. In Fig. 18 also the frequency response can be seen (RC-approx.) which results from the simple equivalent circuit of Fig. 10b).

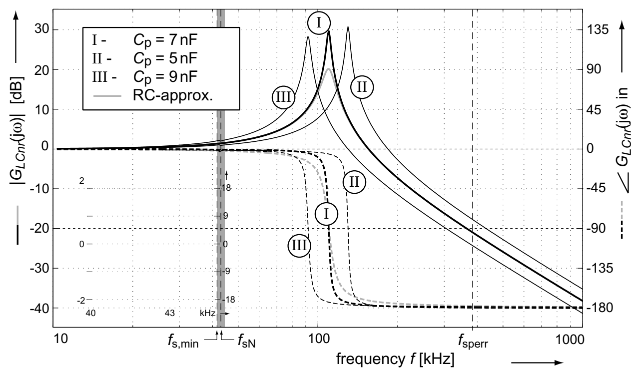

Fig. 18: Output voltage of PWM converter

In case of PWM converters the whole apparent power of the actuator has to be delivered by the inverter and its DC link via the transformer. Due to this aspect PWM inverters are a good choice for sonotrodes which normally have low piezoelectric capacitance ($\omega_{r1} C_P R_m < 1/2$) and low reactive power consumption.

As usual with PWM converters a cascaded control structure is used at which the current is controlled in an inner loop while the voltage of the actuator is controlled in the overlaid loop.

Fundamental frequency has to be set in a separate control loop. At sonotrodes with $\omega_{r1} C_P R_m < 1/2$ the phase shift between the actuator's voltage and current can be controlled to zero. By this measure operation close to resonance is achieved and transfer of reactive power is avoided.

V.B Resonant converters

If the power supply shall be relieved from the high reactive power required by travelling wave motors or other piezoelectric systems with $\omega_{r1} C_P R_M > 1/2$ a compensating coil can be introduced into the circuit. This inductor has to be designed in such a manner that the actuator's capacitance is completed to a resonant circuit which is tuned to the resonant frequency at which the system is operated. Two types of resonant converters having different filter structures have proved to be suitable. They have the following advantages in common:

First, in principle inverter and transformer have to be designed for the active power only which results in low size and low losses of these devices. Second, with regard to the filter characteristic of the resonant circuits low harmonics of the inverter voltage are suppressed and must not be eliminated by use of PWM. Thus the switches of the power converter can be operated with the low fundamental frequency which leads to another reduction of inverter losses.

Considering the power converter and the piezoelectric actuator each containing a resonant systems having varying parameters it can be expected that design of the control is a demanding task. Additional problems arise at travelling wave motors at which coupling between the variables of the two phases exist which cannot be neglected [7].

Converter with low-pass characteristic
(LC converter):

A series resonant converter characteristic results when the filter inductor of the PWM filter is replaced by a resonant inductor [7], [10]. Consequently the circuit is identical with that of the PWM inverter already shown at Fig. 17. Again this circuit has a second-order low-pass characteristic. But now the resonance peak is situated in the frequency range in which the inverter is operated. Consequently the operating point is strongly influenced by variations of the mechanical load R_m and the actuators capacitance which depends on temperature.

As can be seen from the output voltage of a LC resonant converter (i.e. the input voltage of the actuator) depends strongly on frequency. Therefore voltage control can be performed by variation of frequency. By this measure the operating point is shifted on the frequency characteristic, see Fig. 19, which causes an increase or decrease of the filter's output voltage. Realisation of this control scheme is relatively simple but stable operation is only possible at one side of the resonant peak where the gradient has constant sign. Operation on the peak, where the reactive power is minimum, is not possible.

With regard to the great variation of frequency characteristic attention has to be played to avoid undue electrical or mechanical strain. To ensure safe operation the actuator's voltage is normally controlled in an underlaid control loop (which refers to the control loop at PWM converter).

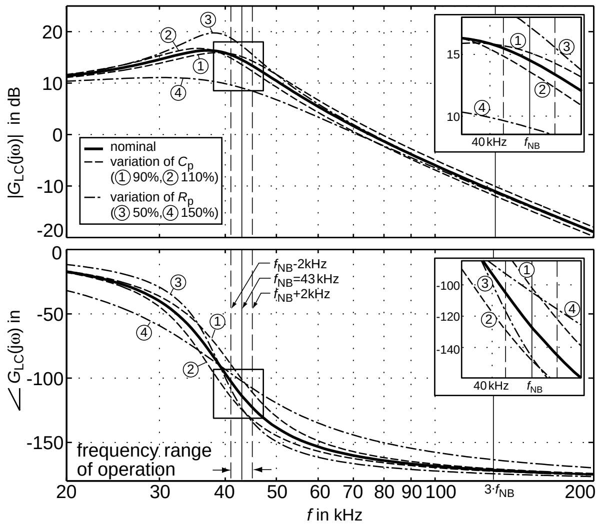

Fig. 19: Output voltage of LC resonant converter

A second possibility for controlling the output voltage of the LC converter is to vary the rectangular input voltage of the resonant filter. For this purpose either the DC link voltage or the width of rectangular half waves can be varied. With these control strategies frequency can be set independently from voltage amplitude which makes possible to operate the system in the peak of the resonant curve.

Converter with band-pass characteristic
(LLCC-resonant converter):

Closed loop control of the actuator's voltage can be avoided by use of a filter with band-pass characteristic [9], [10]. At this circuit, see Fig. 20, the parallel inductance compensates the reactive power of the piezoelectric capacitance. The series resonant circuit is used to complete a voltage divider which is almost independent from frequency in the middle of its pass band. Since only few reactive power is delivered by the inverter devices of the series resonant circuit can be designed for low power only.

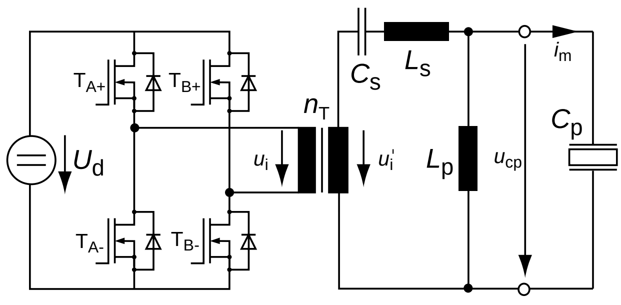

Fig. 20: Full bridge inverter with resonant LLCCfilter

The frequency characteristic of the converter's output voltage is shown at Fig. 21. To achieve symmetrical peaks as shown at the figure series and parallel resonant circuit must be tuned to the operating frequency ($L_P C_P = L_s C_s = \omega_{r1}^{-2}$). The band width depends on the ratio of the capacitances $\alpha = C_s / C_P$ which, for equal resonant frequencies, matches the ratio of characteristic impedances $\alpha = \sqrt{L_p / C_P} / \sqrt{L_s / C_s}$.

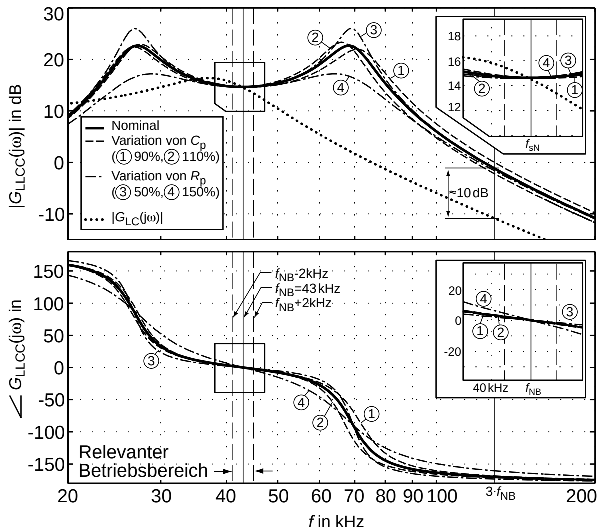

Fig. 21: Output voltage of LLCC resonant converter

The filter of LLCC converter is more complex than a that of LC converter. But it offers more simplicity with regard to control. In the middle of its bandwidth, where the converter is operated, amplitude of output voltage is almost independent of parameter variations. That is why open loop voltage control is possible and an underlaid voltage control is not required. As a consequence better dynamic response is achievable than with LC converter.

At last a possible disadvantage shall be mentioned. Due to the second resonant peak low order harmonics are not suppressed as well as with LC converter. This phenomenon can be observed when small amplitude of fundamental voltage is set by small width of the rectangular inverter voltage, see Fig. 22

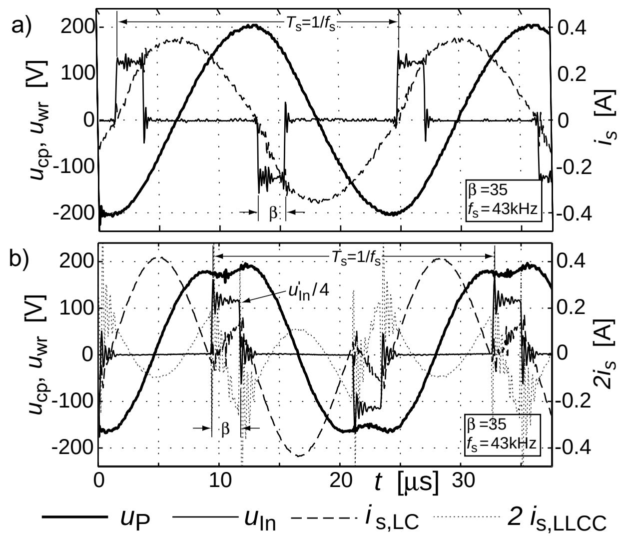

Fig. 22: Wave shapes at small voltage levels
a) LC converter, b) LLCC converter

VI. CONCLUSION

At piezoelectric systems strong dependencies exist between all subsections. They therefore form typical mechatronic systems which demand for an integrated design of the mechanical and electrical subsystem as well as of the control under consideration of the requirements of the specific application.

For this reason close cooperation of mechanical and electrical engineers is expected when an optimum result shall be achieved. On the other hand, considering the equations and figures of Section II. a close relation can be established between wave propagation at piezoelectric systems and wave propagation on electrical transmission lines. And in fact, many results achieved from transmission equations can be applied to the mechanical part of piezoelectric systems.

On the other hand wide knowledge from electrical engineering is required to make a piezoelectric system run. Engineer must not only be familiar with mechanics and power electronics but also depends on experience in control theory and measurement: For control of resonant converters state space averaging has to be applied to sinusoidal signals and at many applications phase-sensitive rectification is required to achieve the actual values of the variables to be controlled.

VII. ACKNOWLEDGEMENT

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