Teichert C., Lindemann A. **Deutschland**

Otto von Guericke Universität Magdeburg

COMPARISON OF POWER ELECTRONIC CIRCUITS FOR PIEZO-ELECTRIC ACTUATORS IN VEHICLE SPRING AND DAMPING SYSTEMS

INTRODUCTION. Adaptive spring and damping systems like they are used in upper class vehicles make the adjustment of the chassis tuning possible with changes of the loading, temperature, wear, driver preference, condition of tires, etc. Resulting out of this driving safety and the traveling comfort is increasing. Therefor a piezo-electrical actuator is used as a valve in the damper. This could be become an efficient and low priced solution also for the employment in middle class and small vehicles. For this system power electronic converter is necessary, which supplies the actuator with energy.

PRINCIPLES of PIEZO-EFFECT. The inverse piezoelectric effect (reciprocal piezoelectric effect) causes a volume-invariant deformation of the crystal with applying of an electrical field (Fig. 1). This deformation is used to actuate a valve gear in the damper to control the volume flow ratings of the gas. Naturally occurring monocrystalline materials such as quartz or tourmaline show a very small piezo effect. Synthetic polycrystalline ferrous electrical sintered ceramics like lead zirconate titanate (PZT) however have better characteristics and therefore are preferentially used for building of actuators. Piezo actuators convert electrical energy directly into mechanical energy. They have response times within millisecond range, reach accelerations of several thousand g and are able to excite large forces. A further advantage is the high resolution in the nanometer range and thus the suitability for highly precise processes [1][2][3]. Piezo actuators produce neither a magnetic field, nor are they affected thereby, because the piezoelectric effect is based on electrical fields. The movement of the piezo actuator works wear-free, since it is based on crystalline solid effects. It doesn't need lubricant and produces no abrasion, thus piezo actuators are suitable also for clean room applications. Also at temperatures close to 0 K the piezoelectric effect exists. A piezo actuator represents electrically a capacitive load. That means that fast voltage changes are linked with high currents.

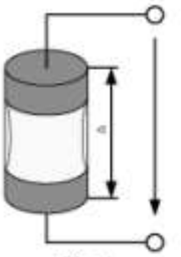

Fig. 1 Piezoelectric effect

Mechanical dynamic of an actuator is affected substantially by the current limit of the power electronic converter. Beyond that the high current peaks during charging and discharging could exert influence on actuator's durability. Acceleration within the ceramic during actuator deflection is in first approximation proportional to the change of the charging current. Rectangular shape of current, results in erratic changes of acceleration with frequency of switching. Therefor, an analog amplifier may charge the capacitive load with a continuous current. Disadvantages of analog circuits are the high electrical losses (reduction of the efficiency), no energy recovery and the increased volume (e.g., bigger head sink required) [4].

For this reason only switching converters are discussed in this work.

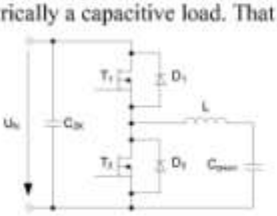

Fig. 2 Phase leg

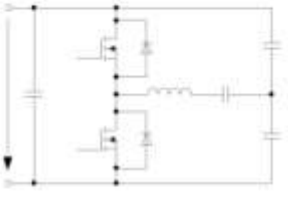

Fig. 3 Half bridge

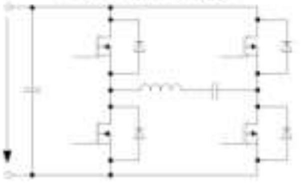

Fig. 4 Full bridge

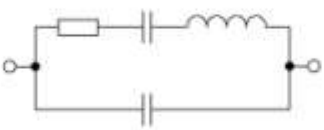

Fig. 5 Equivalent circuit diagram of a piezo-electric device

POWER ELECTRONIC CONVERTER TOPOLOGIES. In the following figures Fig. 2 - 4 possible power electronic converters to drive the actuator are shown [5][6]. The phase leg circuit (Fig. 2) is a simple possibility to drive a piezo actuator. The advantage of this circuit is the small effort, because it has a small number of devices. In this case the piezo actuator will be charged if the transistor T_1 is switched on and it will be discharged again if transistor T_1 is switched off and transistor T_2 is switched on. In addition energy recovery would be possible [7]. The half bridge circuit (Fig. 3) is suitable for a bipolar operation, which makes fast discharging of the piezo actuator possible. The disadvantage of this circuit is that the actuator voltage can only reach the half of the input voltage U_N. This requires high blocking semiconductors. In addition this circuit has a higher complexity due to several devices. The full bridge (Fig. 4) circuit makes also a bipolar operation of the actuator possible; the actuator could be connected alternatively with positive or negative potential. The maximum actuator voltage is equal to the input voltage U_N. The effort of this circuit is higher compared to the phase leg.

MODELING, SIMULATION and EXPERIMENTAL CIRCUIT. The equivalent circuit diagram of a piezo-electric actuator is shown in Fig. 5. The capacitor C_{el} represents the capacity of the dielectric. Parallel to this the serial connection of R_{mech}, C_{mech} and L_{mech} stands for the influence of the mechanical part. In analogy to a spring–mass–damper-system R_{mech} represents the losses inside the piezo, C_{mech} the friction and L_{mech} the effective mass of the actuator [8]. If the piezo actuator is operated far below its first natural frequency, the mechanical influences can be neglected, so the piezo actuator could be described as plate capacitor; its capacity will be calculated from the electrode surface A and the layer thickness d of the piezoelectric material according to [9]:

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot (A/d) \tag{1}$$

The relative dielectric constant ε_r is material specific and can be taken from the data sheet of the piezo ceramic. In a first approximation in this paper to outline the basic results the actuator was considered to be ideal, i. e., R_{mech}, C_{mech} and L_{mech} were ignored. For the elementary investigations at the piezo actuator a phase leg was selected, which is illustrated in Fig. 2. With this circuit arising voltage and current ranges should be determined. The results of a simulation were used to dimension an experimental circuit. The phase leg circuit consists of the main board with semiconductors, driver circuits, inductor and capacitor.

METHOD of CONTROL. With the first method the capacitor will be charged completely, if the transistor T_1 is switched on. The diagrams in Fig. 6 show the comparison between simulation and measurement.

It can be recognized that the actuator voltage and the actuator current oscillate with large amplitude at the beginning. This is the result of the L-C-combination of inductor and capacitive actuator (serial resonant circuit). The simulated and measured graphs fit well.

With this simple control method it is not possible to move the piezo actuator in the desired position. The circuit can only expand or contract the piezo completely. This is not desirable for an employment with piezo actuators as valve, because intermediate values are also demanded, in order to be able to regulate the gas flow. Therefor, another control method was investigated. Thereby voltage and current should not oscillate. That means, as soon as the desired value is reached, the current has to be switched off, in order to prevent an overshooting (Fig. 6).

In this case a simple voltage control at the actuator is not sufficient, because at reaching the desired voltage value the transistor will be switched off and the stored energy in the inductor increases the voltage of the actuator. Therefore the energy of the storage elements is determined and compared with the set point energy value. To realize response times of about 5 µs an additional capacity (220 nF) was switched in parallel to the actuator (33,5 nF).

$$W_{System} = W_C + W_L = \frac{U_{ref}^2 \cdot C_{piezo}}{2} + \frac{I_{ref}^2 \cdot L}{2} \tag{2}$$

The transistor T_1 is switched on until the energy content of the energy storage elements – capacitor and inductor – have equal value together as the set point energy in the piezo actuator, afterwards the transistor T_1 will be switched off and the supply of energy stopped.

Finally the inductor supplies its energy to the piezo actuator until it reaches the set point energy value and the set point voltage value according to $W = U^2 \cdot C/2$. For the first investigations the switching times of the semiconductors were given by a signal source, without a control unit. The result is illustrated in Fig. 7. It shows the comparison between measurement (continued curves) and simulation (dashed curves), those fit well. To discharge the piezo actuator the transistor T_2 will be switched on for a certain time. To determine this switching time t_1 the differential equations of the two conditions (PhaseI: $t_0 \le t < t_1$ → T_2 on; PhaseII: $t_1 \le t < t_2$ → T_2 off, D_1 conducting) have to be set up and solved. In case of an ideal circuit the following solutions result:

$$u_{C_{PhaseI}}(t) = U_{C_{start}} \cdot \cos\left(\frac{t - t_0}{\sqrt{L \cdot C_{piezo}}}\right) \tag{3}$$

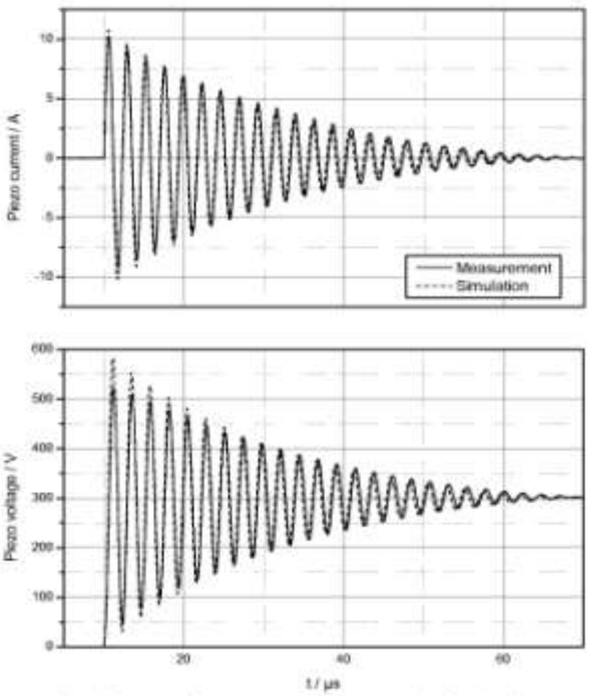

Fig. 6 Comparison measurement and simulation

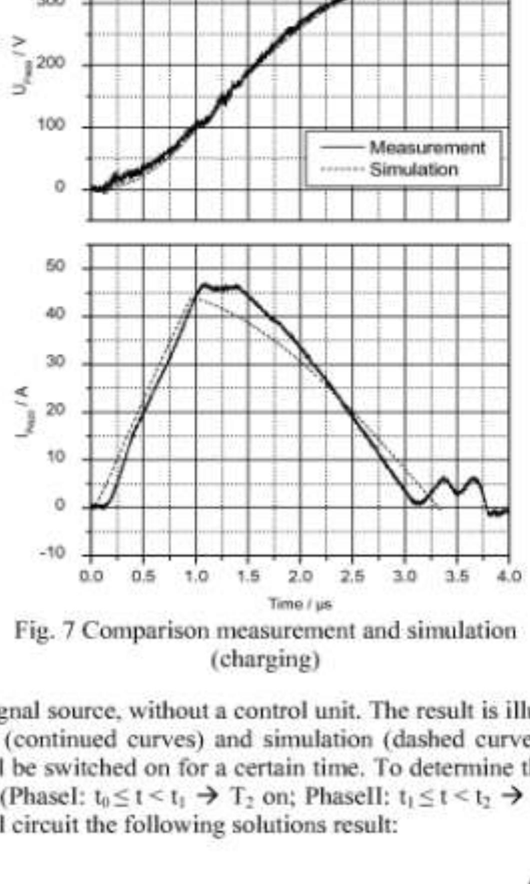

Fig. 7 Comparison measurement and simulation (charging)

$$u_{C_{PhaseII}}(t)=U_N-\left(U_N-U_{C_{start}}\cos\left(\frac{t_1-t_0}{\sqrt{LC_{piezo}}}\right)\right)\cos\left(\frac{t-t_1}{\sqrt{L\cdot C_{piezo}}}\right)-U_{C_{start}}\sin\left(\frac{t_1-t_0}{\sqrt{LC_{piezo}}}\right)\sin\left(\frac{t-t_1}{\sqrt{LC_{piezo}}}\right) \quad (4)$$

$$i_{C_{PhaseI}}(t)=-\sqrt{\frac{C_{piezo}}{L}}\cdot U_{C_{start}}\cdot\sin\left(\frac{t-t_0}{\sqrt{L\cdot C_{piezo}}}\right) \quad (5)$$

$$i_{C_{PhaseII}}(t)=\sqrt{\frac{C_{piezo}}{L}}\left(U_N-U_{C_{start}}\cos\left(\frac{t_1-t_0}{\sqrt{L\cdot C_{piezo}}}\right)\right)\sin\left(\frac{t-t_1}{\sqrt{LC_{piezo}}}\right)-\sqrt{\frac{C_{piezo}}{L}}U_{C_{start}}\sin\left(\frac{t_1-t_0}{\sqrt{LC_{piezo}}}\right)\cos\left(\frac{t-t_1}{\sqrt{LC_{piezo}}}\right) \quad (6)$$

Subsequent, it is possible to determine t_1 with the initial and final values ($U_C(t_2)=U_{C\ setpoint}$, $i_C(t_2)=0$).

After T_2 is switched off the energy in the inductor and in the piezo actuator is decreasing, until the desired set point voltage value is reached in the actuator (Fig. 8).

This method shows good results contrary to the uncontrolled phase leg, but there is a problem, because the switch-on times of the IGBTs are so short, that they are not completely turned on, before the IGBTs switched off again. Fig. 8 shows an example with very short switch-on time of T_2.

In [10] another method is presented. There the model of the current controlled piezo actuator will be described. This viewpoint has the advantage that maximum dynamics could be realized by utilization of the current limit values.

Fig. 9 shows the principle of the standard buck converter [11]. If the transistors T_0 and T_1/T_2 and/or T_3/T_4 are switched on the inductor L_0 will be charged. Afterwards it is possible to control the actuator current direction with the transistor combination T_1/T_4 or T_3/T_2. A condition for the applicability of the view of current source is that during the cycle time the current in the inductance does not change substantially. Therefore a large inductor L_0 and short cycle times are necessary.

In normal operation T_0 is open, so that the actuator gets its energy from the inductor and delivers its energy into the inductor when discharging. Losses are compensated by closing transistor T_0. With this method the actuator current is easy to control.

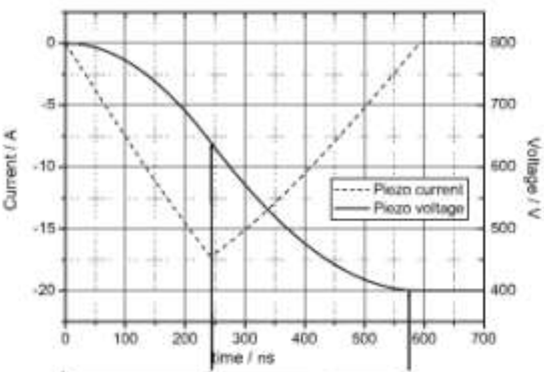

Fig. 8 Discharging of the piezo actuator

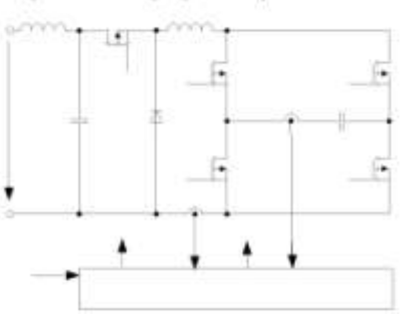

Fig. 9 Schematic diagram of current controlled piezo actuator

CONCLUSION and OUTLOOK. For middle class and small vehicles simple adaptive spring and damping systems are required. This could be achieved by the employment of a piezo actuator as valve.

For a capacitive load like a piezo actuator a control method was investigated. The results demonstrate that the drive of the piezo actuator with a phase leg circuit – without control – is principally possible. In that case the piezo actuator can only deflect completely. In addition unwanted oscillations at the actuator arise.

For an operation free of oscillations a control method was investigated. Therefor energies of the individual storage elements were determined and compared with the set point value. The result shows, that it is possible to realize such a control, but there are although problems with the short switch-on times of the IGBTs. Finally the current controlled piezo was described.

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ACKNOWLEDGEMENT. This work has been supported by: European Commission and European Regional Development Fund.