Energy and Pulse Control Possibilities using Ultra-Tight Integration of Electronics and Piezoelectric Ceramics

Jonny Johansson and Jerker Delsing
EISLAB, Luleå University of Technology
SE-971 87 Luleå, SWEDEN
E-mail: jonny.johansson@sm.luth.se

Abstract—This paper reports on investigations of the electrical energy needed to generate ultrasound pulses with piezoelectric crystals and compares measurements with system simulations using SPICE models. The piezoelectric device used is a 16 mm diameter Pz27 crystal with a nominal resonance frequency $f_{osc,nom}$ of 4.4 MHz. An optimized ASIC driver stage with 5 V supply voltage is mounted directly on the piezoelectric crystal to generate square-wave excitation pulses. The absence of wiring between driver and crystal provides excellent pulse control possibilities. It is shown that the power consumption varies with the excitation pulse width, which also affects the received ultrasound energy in a pulse echo system. To achieve maximum output ultrasound energy, an excitation pulse width of 100 ns = $0.44/f_{osc,nom}$ should be used. At a repetition rate of 1 kHz, the power consumption including losses in the driver stage varies from 96 μ W for an excitation pulse width of 240 ns, up to 126 μ W for an excitation pulse width of 130 ns. The performed SPICE simulations agree well with measured data.

I. INTRODUCTION

Sensor networking and ambient intelligence is an increasingly growing area of research, with whole conferences dedicated to the subject [1]. For portable sensor systems, battery operation and low power consumption are required. In an ultrasound measurement system aimed at this market, the system energy consumption and supply voltage requirements are vital. The excitation of a piezoelectric ultrasound sensor is often performed with a high voltage spike without regard to energy consumption and loss in the system. In a low voltage, low power environment this must be reconsidered. Care must be taken to minimize loss in all parts of the system, and do effective excitation in order to compensate for the very low voltage delivered by a battery supply.

The issue of power consumption for piezoelectric actuators has been investigated by several authors [2], [3]. In these cases the piezoelectric device is driven with frequencies well below the resonance frequency. For a pulse-echo piezoelectric sensor, the excitation is often made with square wave or spike type pulses containing a very broadband spectrum, and the sensor oscillates at its natural resonance frequency. Another area of research is loss reduction for piezoelectric transducers at high vibration amplitude, i.e. where high excitation energies are used [4]. The loss mechanisms involved in a piezoelectric transducer have been analyzed in [5]. For a mobile self-supplied sensor the issue is neither low frequency, nor high

energy excitation. It is the total system power consumption that is important, i.e. the loss generated both in the transducer itself as well as in the associated driving electronics.

This paper reports on measurements and simulations of the electrical energy required to generate ultrasound pulses with piezoelectric crystals, and compares measurements with system simulations where SPICE models are used. The motivation behind the work is twofold: First, we want to find reliable approximations for the minimum power consumption of a driver/crystal system. Second, we want to verify that available SPICE simulation models can predict the energy consumption. The choice of driving pulse waveform to minimize system energy consumption is discussed. Measurements and simulations of the power consumption and received echo energy in a pulse echo system are presented. It is shown that the absence of wiring and interconnections between the electronics and the driven crystal in the setup used give excellent pulse control possibilities, without the need for broadband electrical matching networks.

II. PULSE SHAPE CONSIDERATIONS

The type of pulse shape used for the excitation of a piezoelectric ceramic is highly decisive for the complexity and power consumption of the driving electronics. A very simple pulse shape to generate is a square wave, requiring only a small number of logic gates and two main driver transistors that are switched between on and off state. This pulse shape also generates ultrasound pulses with high energy content if the correct pulse width is chosen [6]. Another choice is to use a gated sinusoidal waveform or even an arbitrary waveform. The use of a sinusoidal waveform would seem energy efficient for a capacitive sensor such as the piezoelectric disc used in this paper. A capacitive load will not draw active power from a sinusoidal voltage source, unless there are imaginary components in the dielectric constant. However, when we apply a system view incorporating also the power consumption of the driver electronics, it is clear that the losses in a sinusoidal case occurs in the driver itself. The charge delivered to the capacitive sensor will always have to be dumped into ground, unless an active dc-dc supply with very high update rate is used to discharge the sensor. It remains to investigate the use of such devices for this purpose. An arbitrary waveform

generator will require a high speed D/A converter that also consumes power, buffered by a high speed amplifier to drive the capacitive load. With this background the choice for the investigations performed in this paper has been to use a square wave excitation pulse.

III. ESTIMATE OF ENERGY CONSUMPTION

A piezoelectric ceramic disc can, as an approximation outside of its resonance regions, electrically be viewed as a parallel plate capacitor with a capacitance

$$C_0 = \frac{A\epsilon_0 K}{d}. \quad (1)$$

Here ϵ_0 is the permittivity in free air, K is the dielectric constant of the material, A is the area of the disc, and d is its thickness [7]. The governing parameter here is K , which for a piezoelectric material varies with frequency and mechanical state for the material. K is traditionally measured for two situations, *clamped* and *free*. The free dielectric constant K^T is often measured at 1 kHz where the disc is free to move. The clamped dielectric constant K^S on the other hand is measured on a frequency above all resonances and their harmonics (several MHz), where inertia blocks the movement of the disc. The values of K^T and K^S for the Pz27 disc used in this paper are given in table I.

The complete analysis of energy consumption in a piezoceramic material is complex, a thorough analysis of loss mechanisms involved in piezoelectric transducers can be found in [5]. A rough estimate can however be performed using the effective capacitance values of the piezoceramic disc, as these actually include mechanical effects. A capacitance C which is charged and discharged with a repetition frequency f will draw an electrical power $P = fCV^2$. When in a free condition and when full mechanical energy is developed in the piezoceramic disc used in this paper, a maximum electrical power of $164 \mu\text{W}$ should be consumed at a repetition frequency of 1 kHz. In a clamped state when no mechanical energy is developed, a minimum electrical power of $83.5 \mu\text{W}$ should be consumed.

In this paper we are interested in not only the power consumption of the piezoelectric disc itself, but also the loss in its associated electronics. Thus, losses introduced in the electronics must be added to the minimum estimated power consumption calculated above to get the system power consumption.

TABLE I
DATA FOR THE PZ27 DISC USED IN THIS PAPER.

Parameter	Notation	Value
Radius	a (m)	0.008
Thickness (nominal)	len_{nom} (m)	$487 \cdot 10^{-6}$
Thickness (used)	len (m)	$470 \cdot 10^{-6}$
Free Dielectric Const.	K^T (As/Vm)	1800
Clamped Dielectric Const.	K^S (As/Vm)	914
Frequency (nominal)	$f_{osc,nom}$	$4.44 \cdot 10^6$
Frequency (measured)	f_{osc}	$4.6 \cdot 10^6$

Fig. 1. Block schematic of the measurement setup.

Fig. 2. The driver chip mounted on a 16 mm diameter Pz27 disc.

IV. SYSTEM SETUP

A. Experimental

A block schematic of the setup is shown in Fig. 1. The sensor is a circular piezoceramic disc with properties as tabulated in table I [8]. A custom built driver chip which generates a square wave output pulse is used to generate an excitation pulse [9]. The driver chip is mounted directly at the piezoceramic disc, as shown in Fig. 2 [10]. The width of the excitation pulse is set by an external square wave generator. Power is supplied by a Keithley 2400 series Sourcemeter set at 5 V. The power supply cabling is decoupled at the piezoceramic disc. The mean current consumption is measured with the built in amperemeter in the Sourcemeter instrument. The load on the output of the square wave generator is two small CMOS gates, that yield a capacitance of a few tens of fF. Thus, the power consumed by the charging and discharging of this gate capacitance is ignored. The excitation and the received echo are measured directly at the disc with an attached oscilloscope with low load active probes ($C_p < 2 \text{ pF}$, $R_p = 1 \text{ M}\Omega$). As the probes draw some current due to the relatively low resistance they were disconnected during the power measurements. Measurements and simulations have been performed with the piezoceramic disc in two states; free and loaded on one side. For the free measurements the disc is supported only by the attached cabling with air on both sides. In this setup the radiated ultrasonic energy is negligible, as there is a large mismatch in acoustic impedance between Pz27 and air. The main purpose of this arrangement is to achieve a well defined state to be able to compare theoretical approximations with measured data. In order to achieve a pulse echo system the disc was attached with acoustic couplant to a 21 mm thick plate of

Fig. 3. Excitation signal for pulse widths of 115 ns and 230 ns.

Plexiglas (PMMA). An ultrasound pulse is then generated into the PMMA, and reflected back to the piezoelectric disc at the PMMA-air interface. Also here the back side of the piezoelectric disc is unloaded (air).

B. Simulation environment

Simulations were performed using the Cadence Spectre simulation engine. Spectre has the possibility to run netlists created for SPICE, enabling the use of models previously developed for SPICE. The models used for the simulation of the piezoceramic disc and the propagation medium are taken from van Deventer [11]. Diffraction loss is included in the model [12], making it possible to achieve correct absolute amplitudes in received echoes. Simulation of the electronics is made using transistor models from the chip manufacturer. The temperature for the simulations is 25 °C.

V. RESULTS

The extreme proximity of the driver to the crystal provides very clean excitation pulses, as shown for 115 ns and 230 ns excitation pulses in Fig. 3. The pulse widths chosen are slightly longer than $T_{pz}/2$ and T_{pz} respectively, where $T_{pz} = 225$ ns is the period time of the calculated self-resonance frequency of the piezoelectric crystal. It can be seen that the ringing of the crystal after excitation is very low for the excitation with a pulse width of 230 ns. This is due to the fact that the second (rising) edge of the excitation pulse is applied out of phase to the ringing of the crystal, thus effectively attenuating the ringing. On the other hand, for the excitation with 115 ns pulse width the second edge is applied in-phase with the crystal oscillation, thus increasing the ringing of the crystal.

With the crystal non-rigidly mounted as in these measurements it is subject to non-wanted radial and flexural modes of oscillation [13]. These oscillations remain also to some extent at the time of arrival of the echo after about 15 μs.

Fig. 4. Received AC coupled and filtered echo for excitation pulse widths of 115 ns and 230 ns.

Thus, a bandpass filter has been applied in Matlab to remove these oscillations from the received echoes. Fig. 4 shows the filtered received echoes for the excitations discussed above. The amplitude of the received echoes verify that the amount of energy transmitted into the material is very low for the excitation pulse width around T_{pz} .

To get a better view of how the received echo energy varies with the excitation pulse width, this was varied in 10 ns increments, and relative energy content of the received pulse echo was measured and simulated. The pulse energy content was calculated as

$$W_p = \int_{T_p} V_p(t)^2 dt \quad (2)$$

where T_p is the duration of the received pulse and $V_p(t)$ is the momentary measured voltage at the piezoelectric disc. The results are shown in Fig. 5. The measurements verify that the pulse energy content varies with the excitation pulse width. Further it is seen that the energy content predicted by the simulation agrees very well with the measured results.

The power consumption of the device was measured and simulated for various excitation pulse widths at a pulse repetition frequency of 1 kHz. The results are shown in Fig. 6. It is clearly seen that the consumed power varies as the excitation pulse width changes. Power measurements were also performed for a free disc. The results from these measurements are included in Fig. 5. Another measurement was made on the free disc using a square wave signal with 50% duty cycle at 1 kHz for excitation. The intention with this measurement was to explore the energy consumption when the piezoelectric material was free to settle between positive and negative excitation edges, i.e. to achieve a true free state also during the pulse duration. This measurement gave a power consumption of 158 μW. When the test was repeated in the simulator, it was found that the long simulation times required

Fig. 5. Received pulse energy content for various excitation pulse widths.

(> 1 ms) generates a runaway behavior of the current into the model of the piezoelectric device. At 1 ms simulation time after excitation, the current into the device has grown up to several hundreds of μA . It then grows exponentially to several hundred amperes within another couple of ms, whereafter the simulation fails. It should however be noted that the model works without errors for the short ($\ll 1$ ms) simulation times that are normally used.

Power consumption should occur in the system only during switch operation, i.e. the power consumption should be linearly dependent on the repetition rate. Measurements were made on the free crystal for repetition frequencies of 100 Hz and 1 kHz with an excitation pulse width of 120 ns. The power consumption was $12.8 \mu\text{W}$ and $128.5 \mu\text{W}$ respectively. This verifies that the power consumption is dynamic only, with minimal static loss in the system.

In the measurements presented above it is not possible to separate losses in the driver stage from the overall power consumption. Simulations do however show that the power loss in the driver stage itself is about $3 \mu\text{W}$ at a repetition frequency of 1 kHz.

VI. DISCUSSION

A. Excitation pulse shape

The fact that there is no cabling between the driver chip and the driven crystal yields a very clean excitation pulse, as shown in Fig. 3. This can be compared with a situation where a coaxial cable is used and parasitic inductance and capacitance influence the behavior of the excitation pulse [14]. Even a short length (7 cm) coaxial cable introduces unwanted oscillations, whereas a long cable (2 m) gives rise of several reflections affecting the crystal. One way to counteract this behavior would be to introduce broadband matching network

Fig. 6. Power consumption of driver and crystal at a repetition frequency of 1 kHz.

in the transducer end of the cable [15], [16]. These matching networks are most often analyzed in the frequency domain

In this paper a different approach is taken. The driver electronics are moved and placed directly on the transducer itself. This eliminates the need for cabling, and the matching issue can be turned from impedance matching in the frequency domain, to control of time constants and rise and fall times in the time domain. The transducer can be viewed as a capacitive load directly connected to the driver stage. For a push-pull driver stage as used in this paper, the issue is to achieve short enough rise and fall times for the charging and discharging of the transducer.

The driver chip and its associated bond pads cover a surface of about (4 x 6) mm. Most likely the attachment of chip and bond pads will cause a minor disturbance of the radiated beam pattern, but for the investigations in this paper this effect has been judged to be negligible.

B. Power consumption and pulse energy

The consumed power reaches a local minimum for $t_{exc} = 240 \text{ ns} \approx T_{pz}$. At this pulse width also the received pulse energy shows a local minimum. This is reasonable, as the second edge of the excitation is applied out of phase in relation to the oscillation of energy within the piezoceramic disc. This attenuates further ringing, and minimizes the energy consumption. Although at a local minimum, the energy consumed is slightly higher than the estimated minimum. This is also reasonable, as some mechanical energy is produced during the complete phase that the crystal is allowed to oscillate. Further, some energy is lost within the driver electronics itself.

As t_{exc} is decreased towards $t_{exc} \approx T_{pz}/2$, both power consumption and pulse energy increases, due to the fact that the second edge of the excitation more and more is moving in-phase with the oscillation in the crystal. The power consumption reaches a local maximum for $t_{exc} \approx 130 \text{ ns} >$

$T_{pz}/2$, while the received pulse energy has its maximum at $t_{exc} \approx 100 \text{ ns} < T_{pz}/2$. The power consumption decreases about 8% when t_{exc} goes from 130 ns to 100 ns, while the received pulse energy increases about 13%. This shows that a fair amount of power can be saved, and pulse energy increased, by a careful selection of excitation pulse width.

The power consumption measured for a free crystal agrees well shape-wise with the power measured for the loaded crystal. However, it can be seen that its first local maximum is somewhat higher and the second substantially higher than the ones achieved in the pulse-echo system. One probable explanation for this behavior is that the crystal does not lose mechanical energy during the time up to the second edge of the excitation pulse. Thus the stored mechanical resonance energy in the crystal can further increase the effect of the second excitation edge, and also increase the subsequent ringing and energy consumption of the device.

For both consumed power and received echo energy, the simulations performed yield reasonable agreement with measured data.

The power consumption of the square wave generator that controls the driver stage has not been included in the measurements. As concluded above the generator drives an extremely small load. For a complete system implementation, the timing circuitry for pulse generation will also be included on chip. Simulations show the power consumption of a timing circuit to be in the order of a few μW for a repetition frequency of 1 kHz.

C. Measurement and simulation accuracy

The used oscilloscope has 8 bits of resolution. It is however used at a high oversampling ratio, which yields a higher number of effective bits. Several measurements performed for identical input data show the variance in the measurements to be below 1%. Thus, error bars are not included in the presented figures to increase clarity of the graphs.

For the simulations, the variance is obviously zero since no parameters are changed. It should however be noted that the simulation result is highly dependent on material parameters, e.g. K^T which directly affects the power consumption. As properties for the piezoceramic material are given with tolerances ranging from $\pm 2.5\%$ up to $\pm 10\%$, it should not be unexpected to see simulation results with nominal values that deviate from measurements. However it should still be expected to see the correct behavior in simulated data. For the simulations presented in this paper nominal material data has been used in all places except for transducer thickness. This has been adjusted slightly as shown in table I to achieve the correct resonance frequency for the simulated crystal.

VII. CONCLUSIONS

In this paper we have presented measurements and simulations of the minimum electrical power drawn to drive a piezoelectric crystal together with its associated electronics. A custom built ASIC driver stage has been mounted directly at the piezoelectric crystal. It is shown that the absence of cabling between

the driver stage and the piezoelectric device give excellent pulse control possibilities. The transmitted ultrasound pulse energy as well as the consumed electrical power varies as a function of the excitation pulse width, with maxima at an excitation pulse width around half the natural oscillating period time of the crystal. The same behavior is predicted by simulations performed with SPICE models of the piezoelectric devices. Maximum transmitted ultrasound energy in a pulse echo system was found at an excitation pulse width at 100 ns for a piezoelectric disc with 4.4 MHz center frequency. For the 16 mm diameter disc the power consumption including losses in the driver stage is only 12.8 μW from a 5 V supply at a repetition frequency of 100 Hz.

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