ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

THE RISE OF ULTRASONIC SYSTEM EFFICIENCY BY USING MISCELLANEOUS ADAPTATION SCHEMES BETWEEN ELECTRONIC GENERATOR AND PIEZOELECTRIC TRANSDUCER

Odobescu Grigore Liviu, Odobescu Rares Alexandru

Institute of Solid Mechanics; Constantin Mille street, no.15, 010141 Bucharest, Romania
e-mail: g_odobescu@yahoo.com

Abstract
The ultrasonic systems constituted from ultrasonic piezoelectric transducers and other elements of acoustics chain are supplied from electronic generators, which works in commutation. The commutation-working regime assures a high efficiency for electronic generator, but generates a large spectrum of frequency. The paper presents miscellaneous adaptation schemes between generator and piezoelectric transducer, which raise the efficiency transformation of electrical energy into mechanical energy in function of frequency and acoustic charge. It is presented and characterised comparative these adaptation schemes. It is given the diagrams of characterisation and the experimental results obtained from author.

INTRODUCTION

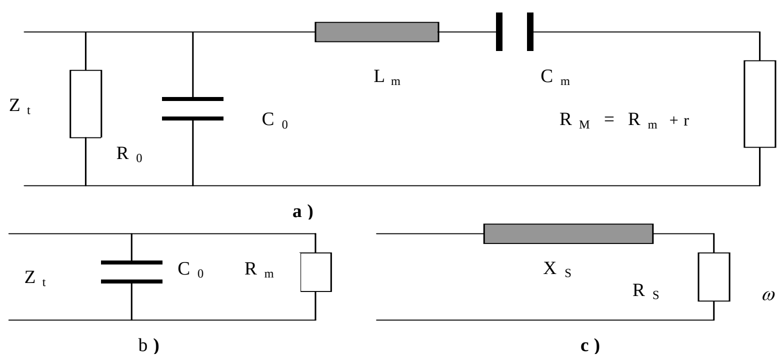
The commutation-working regime determines a minimal dissipated power for collector circuit of power transistor and a high efficiency (85÷98)%. The signal will be rectangular and higher odd harmonics of signal will have a considerable weight. This fact will conduct to supplementary losses, depending on the harmonic level in useful signal and the adaptation circuit used.

PRINCIPLE OF OPERATION

The principle of operation was described in [1]. We found that the total efficiency of generator, without adaptation scheme, for all n harmonics, will be the relation (2). We can see that the generator efficiency depends by the charge - Z_S - and by the internal resistance of generator - r_i -. In fig.1 it is given the equivalent electric scheme in the case of a piezoelectric transducer -a-, at series resonance frequency -b- and series transformation of this scheme -c-. For to minimise the variations of transducer reactance due of acoustic charge variations it put in parallel on transducer an extern capacitor which not varies with work conditions. It is usual noted C_P. In this manner rises the capacity C_0 of transducer with a capacity, which not varies with work conditions, and existing variations will be, in percentage, reduced. The value of this capacity is usually: $C_P = C_0 \Rightarrow$ for little variation of acoustic charge (in case of ultrasonic cleaner when acoustic charge can varies from ten times) and $C_P = 10 \cdot C_0 \Rightarrow$ for large variation of acoustic charge (in case of ultrasonic welder when acoustic charge can varies from one hundred times). The series transformation of equivalent electric scheme for piezoelectric transducer is given in fig. 1c. The calculating relations for elements are:

$$X_S = \frac{X_P \cdot R_P^2}{X_P^2 + R_P^2} \text{....and....} R_S = \frac{X_P^2 \cdot R_P}{X_P^2 + R_P^2} \qquad (1)$$

The vibration amplitude of piezoelectric transducer is proportional with motion current through mechanic branch of equivalent electric scheme (fig.1a). The exciting generator must controls the value of this current to avoid over-demands mechanic in conditions of variable acoustic charge.



$$X_P = \frac{1}{\omega_S \cdot C_0}$$
$$R_P = r$$
$$X_S = \frac{X_P \cdot R_P^2}{X_P^2 + R_P^2}$$
$$R_S = \frac{X_P^2 \cdot R_P}{X_P^2 + R_P^2}$$
$$\omega_S \cdot L_m = \frac{1}{\omega_S \cdot C_m}$$

Figure1- The electric equivalent schemes for piezoelectric transducer.

The purport for used symbols is:

- C_0 - the capacity of ceramic material included between armatures with a dielectric non-piezoelectric having the same relative permittivity ε_r like piezoelectric material;
- R_0 - the resistance represents the dielectric losses $tg\delta = 1/\omega R_0 C_0$;
- L_m - the inductance proportional with piezoelectric material mass;
- C_m - the capacity proportional with mechanic stiffness of piezoelectric material or with elastic compliance s - $s_{ij}=S_i/T_j$;
- R_m - the resistance proportional with mechanic losses;
- r - the charge resistance - radiation -; r=0 in the case of air charge.

The piezoelectric transducer has a capacitance attitude to higher frequency than resonant frequency and their efficiency subtract for different frequencies than resonant mechanic frequency. Therefore the adaptation scheme of electronic generator, working in commutation, must has the following requirements:

- the transformation of electronic generator from tension source having constant amplitude to current source having constant amplitude at work frequency, to controls transducer vibration amplitude;
- the realisation of inductive character of charge to higher frequencies in report with work frequency for to decrease the values of commutation currents through electronic devices

The capacity compensation represents the simply circuit which responds to this requirement. Conform with relations (1) if C_P=0 (therefore it isn't an additional capacity parallel on piezoelectric transducer) we have big value from $X_P=\dfrac{1}{\omega C_P}$ and we can write: $R_{S1}=\dfrac{R_P X_P^2}{X_P^2}\approx R_P$; $X_{S1}=\dfrac{R_P^2}{X_P}$. If we have an additional capacity, in parallel on piezoelectric transducer $C_P\neq 0$ (par example C_P=16nF), we have a small value for X_P. We can write: $R_{S2}=\dfrac{X_P^2}{R_P}$; $X_{S2}=\dfrac{R_P^2 X_P}{R_P^2}=X_P$. These variations are given in fig.2 where it is taken for C_0=4 nF, f_S=40kHz, R_m=100Ω and r was varied from 10 to 10 in the range (0-5000). It is observed that presence of C_P in parallel on transducer decreases the variations of X_{S2} and R_{S2} in report with the case C_P=0 when we have the curves X_{S1}, R_{S1}.

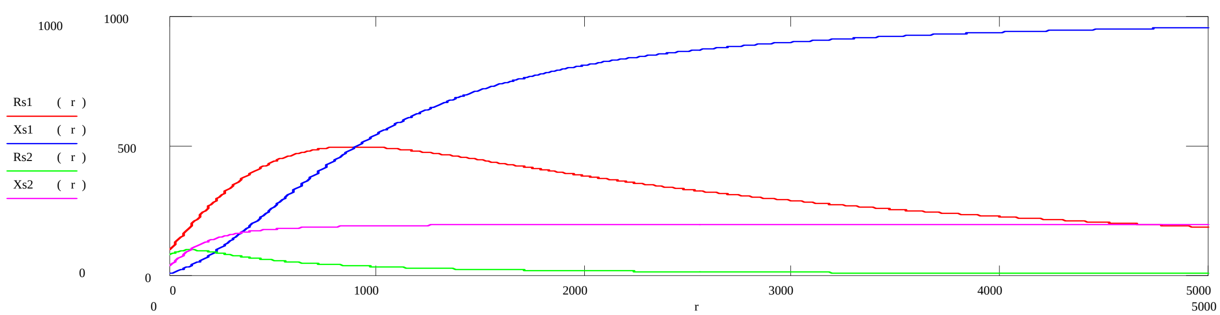


Figure 2. The variation of impedance in function of r, having, as parameter, the variation of compensation capacity.

Let us analyse the piezoelectric transducer with equivalent circuit in fig.3. The circuit, for fundamental frequency (n =1) becomes concordant with fig.4.

The input impedance of transducer, for fundamental frequency (n = 1), will be:

$$Z_t\,(r, n{=}1) = \frac{R}{\sqrt{1+\omega_0^2\cdot R^2\cdot C_0^2}}\cdot e^{j\,arctg(-\omega_0 C_o R)} \qquad (2)$$

Where: ω_0 - is the pulsation at resonance frequency;

R - is the transducer resistance at resonance R= $\frac{(R_m + r)R_0}{R_m + r + R_0}$

The efficiency will be:

$$\eta_g = \frac{\sum_{n=1}^{\infty} P_n}{\sum_{n=1}^{\infty} P_{tot}} = \frac{1}{1 + \frac{r_i \cdot \sum_{n=1}^{\infty} \frac{1}{n^2} \cdot \frac{|\alpha_n|^2}{|Z_{Sn}|^2}}{\sum_{n=1}^{\infty} \frac{1}{n^2} \cdot \frac{|\alpha_n|^2}{|Z_{Sn}|} \cdot \cos\varphi_n}} \quad (3)$$

The circuit becomes, for odd higher harmonics frequency (n ≥ 3), in concordance with fig.4. So that:

$$Z_t\,(r, n \geq 3) = \frac{R_0}{\sqrt{1 + n^2 \cdot \omega_0^2 \cdot C_0^2 \cdot R_0^2}} \cdot e^{jarctg(-n\omega_0 C_0 R_0)} \quad (4)$$

According as the frequency increases (n≥ 3) the transducer will become such as a capacity having the equivalent circuit given in fig.4. For a suitable efficiency, the transducer impedance Z_t (r, f) will be compensated with an adaptation scheme so at the fundamental frequency, the charge resistance of generator will become active (cosφ=1) and for higher harmonics this impedance will increase as much as possible. The circuit of adaptation scheme is showed in the fig.3. Let's note: $\omega_0=2\pi f_0$ - fundamental pulsation of piezoelectric transducer; $\Omega_n=n\cdot\omega_0$; n–number of harmonics. In complex we have: $Z_{rm}(r,n)=(R_m+r)+j(\Omega_n L_m-\frac{1}{\Omega_n C_m})$ and in polar ordinates: $Z_{rm}(rn)=\sqrt{(R_m + r)^2 + \left(\Omega_n L_m - \frac{1}{\Omega_n C_m}\right)^2}\, e^{j\cdot arctg\frac{\Omega_n L_m - \frac{1}{\Omega_n C_m}}{R_m + r}}$. The impedance of transducer for fundamental frequency [n=1, $Z_m=(\omega_0 L_m-\frac{1}{\omega_0 C_m})\approx 0$ and $R_0 >> R_m + r$] will be: $Z_{1t}(r) = \frac{R_m + r}{\sqrt{1 + \omega_0^2 \cdot (R_m + r)^2 \cdot C_0^2}} \cdot e^{j\cdot arctg(-\omega_0 R_0 C_0)}$

The impedance of piezoelectric transducer in function of harmonics [Z_{rm}(r, n) >> R_0] will be: $Z_t(n) = \frac{R_0}{\sqrt{1 + \Omega_n^2 \cdot C_0^2 \cdot R_0^2}} \cdot e^{j\cdot arctg(-\Omega_n R_0 C_0)}$

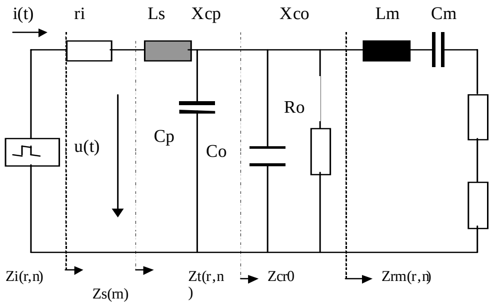


Figure 3. Electrical circuit generator-classical series adaptation scheme – piezoelectric transducer

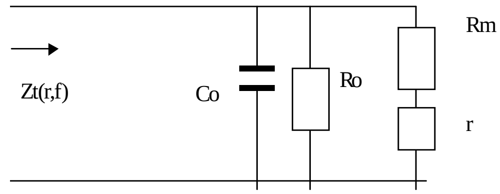


Figure 4. Electrical circuit of piezoelectric transducer for fundamental frequency (n=1) and for odd harmonic frequency

The piezoelectric impedance [$Z_{1t}(t)$ or $Z_t(n)$] and C_P, L_S will be, for harmonic and fundamental frequency:

$$\begin{cases} XCp\,(n) = \dfrac{1}{\Omega_n Cp}\cdot e^{j\cdot arctg\,\frac{3\pi}{2}} \\ XLs\,(n) = \Omega_n \cdot Ls \cdot e^{j\cdot arctg\,\frac{\pi}{2}} \end{cases} \;\text{.....}\;and\;\text{.....} \begin{cases} X1Cp\,(1) = \dfrac{1}{\omega_0 Cp}\cdot e^{j\cdot arctg\,\frac{3\pi}{2}} \\ X1Ls\,(1) = \omega_0 \cdot Ls \cdot e^{j\cdot arctg\,\frac{\pi}{2}} \end{cases}$$

The charge impedance of piezoelectric transducer and adaptation scheme, for fundamental and harmonic frequency, will be:

$$Z1s(r) = X1Ls + \frac{Z1t(r)\cdot X1Cp}{Z1t(r) + X1Cp}\text{...}and\text{...}Zs(n) = Xls(n) + \frac{Zt(n)\cdot XCp(n)}{Zt(n) + XCp(n)}$$

Divider coefficient and efficiency for fundamental frequency (n=1) will be:

$$\alpha 1(r) = \frac{Z1s(r)}{ri + Z1s(r)}\text{.......}and\text{.......}\eta 1(r) = \frac{Z1s(r)}{ri + Z1s(r)}$$

Divider coefficient for n harmonic frequency will be: $\alpha n(n) = \dfrac{Zs(n)}{ri + Zs(n)}$. The efficiency in function of harmonic number will be calculate in following mode:

→ The absorbed current for n harmonic frequency: $Iabsn = \dfrac{E}{ri + Zs(n)}$

→ The absorbed current for fundamental frequency: $Iabs0 = \dfrac{E}{ri + Z1s(r)}$

The efficiency at n harmonic frequency report to fundamental frequency will be $\eta(n) = \dfrac{Pn}{P0} = \dfrac{ri + Z1s(r)}{ri + Zs(n)}$. The electric circuit of the new adaptation scheme it is presented in fig.5. The impedance of piezoelectric transducer for fundamental frequency [n=1, Zm=($\omega_0 L_m - \dfrac{1}{\omega_0 C_m}$)≈0 and $R_0 >> R_m + r$] will be:

$$Z_{1t}(r) = \frac{R_m + r}{\sqrt{1 + \omega_0^2\cdot(R_m + r)^2\cdot C_0^2}}\cdot e^{j\cdot arctg(-\omega_0 R_0 C_0)}$$

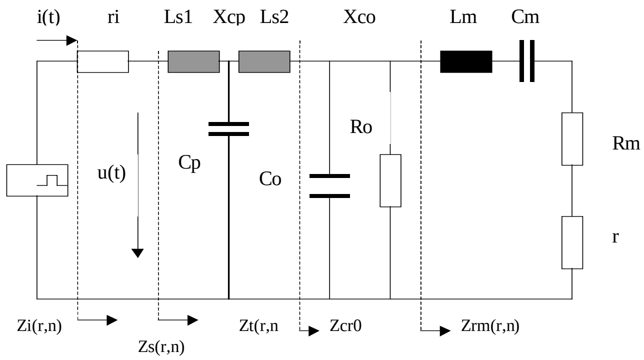


Fig.5. Electrical circuit of generator – new series adaptation scheme – piezoelectric transducer.

The impedance of piezoelectric transducer in function of harmonics [Z_{rm}(r, n) >> R_0] will be: $Z_t(n) = \dfrac{R_0}{\sqrt{1+\Omega_n^2 \cdot C_0^2 \cdot R_0^2}} \cdot e^{j \cdot arctg(-\Omega_n R_0 C_0)}$

The piezoelectric impedance [Z_{1t}(t) or Z_t(n)] and C_P, L_S will be, for harmonic and fundamental frequency:

$$\begin{cases} XCp(n) = \dfrac{1}{\Omega_n Cp} \cdot e^{j \cdot arctg \frac{3\pi}{2}} \\ XLs1(n) = \Omega_n \cdot Ls1 \cdot e^{j \cdot arctg \frac{\pi}{2}} \\ XLs2(n) = \Omega_n \cdot Ls2 \cdot e^{j \cdot arctg \frac{\pi}{2}} \end{cases} ...and... \begin{cases} X1Cp(1) = \dfrac{1}{\omega_0 Cp} \cdot e^{j \cdot arctg \frac{3\pi}{2}} \\ X1Ls1(1) = \omega_0 \cdot Ls1 \cdot e^{j \cdot arctg \frac{\pi}{2}} \\ X1Ls2(1) = \omega_0 \cdot Ls2 \cdot e^{j \cdot arct \frac{\pi}{2}} \end{cases}$$

The charge impedance of piezoelectric transducer and dipole adaptation, for fundamental and harmonic frequency, will be:

$$Z1s(r) = X1Ls1 + \frac{X1Cp \cdot [Z1t(r) + X1Ls2]}{Z1t(r) + X1Ls2 + X1Cp}$$

$$Zs(n) = Xls(n) + \frac{XCp(n) \cdot [Zt(n) + XLs2(n)]}{Zt(n) + XLs2(n) + XCp(n)}$$

Divider coefficient and efficiency for fundamental frequency (n = 1) will be: $\alpha 1(r) = \dfrac{Z1s(r)}{ri + Z1s(r)}$ ...*and*...$\eta 1(r) = \dfrac{Z1s(r)}{ri + Z1s(r)}$. Divider coefficient for n harmonic frequency will be: $\alpha n(n) = \dfrac{Zs(n)}{ri + Zs(n)}$. The efficiency for n harmonic frequency report to fundamental frequency: $\eta(n) = \dfrac{Pn}{P0} = \dfrac{ri + Z1s(r)}{ri + Zs(n)}$

THE OBTAINED RESULTS

This study concerning the efficiency of ultrasonic systems using miscellaneous adaptation schemes. The following calculation programs accomplished it:

- the total impedance of piezoelectric transducer and adaptation scheme for fundamental frequency, with classical adaptation scheme - Z1s(r) and with new adaptation scheme – Z1sa (r) – fig. 6.
- the total impedance of piezoelectric transducer and adaptation scheme for n harmonic frequency, with classical adaptation scheme - Zs(n) and with new adaptation scheme – Zsa (n) – fig. 7.
- the efficiency as a function of acoustic charge r for fundamental frequency, with classical adaptation scheme η1(r) and with new one η1a(r) – fig 8.
- the efficiency as a function of acoustic charges r for n harmonic frequency, with classical adaptation scheme η(n) and with new one ηa(n) – fig 9.

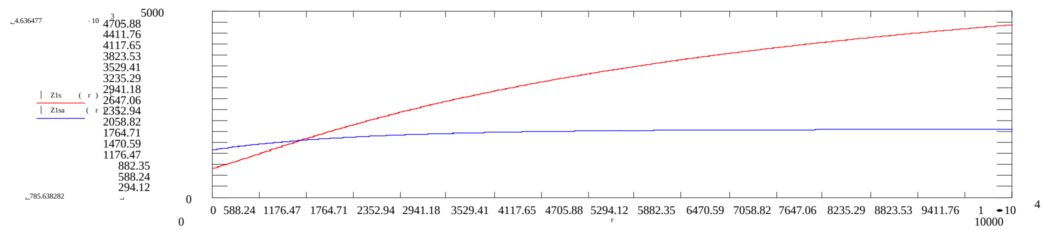


Fig.6. The total impedance of piezoelectric transducer and adaptation scheme for fundamental frequency, with classical adaptation scheme - Z1s(r) – red - and with new adaptation scheme – Z1sa (r) – blue.

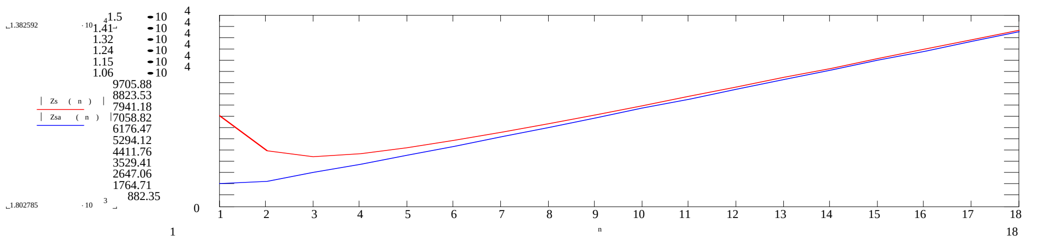


Fig.7. The total impedance of piezoelectric transducer and adaptation scheme for n harmonic frequency, having a classical adaptation scheme - Zs(n) –red- and having a new adaptation scheme – Zsa (n) – blue -.

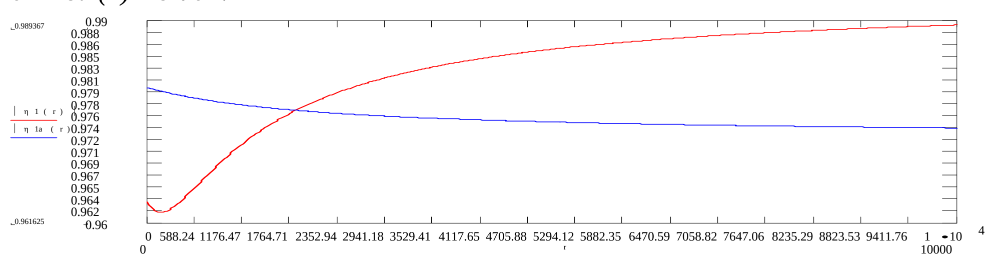


Fig.8. The efficiency as a function of acoustic charge r for fundamental frequency, having a classical adaptation scheme η1(r) – red- and having a new one η1a(r) – blue-.

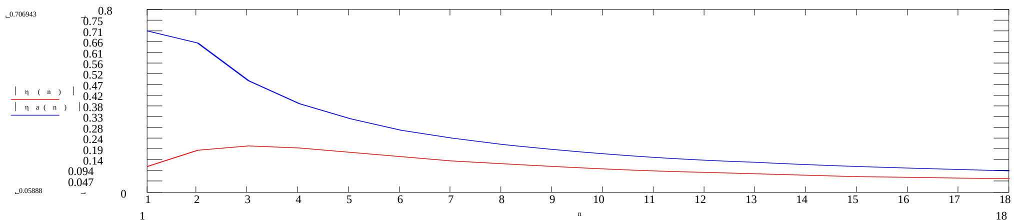


Fig.9. The efficiency as a function of n harmonic frequency having a classical adaptation $\eta(n)$ – red- and having a new one $\eta a\ (n)$ – blue-.

All the calculations were accomplished by means of MATHCAD programs, based on the formulas presented in this paper. As piezoelectric transducer it was tacked the TGUS-150-40-2 type, built at the Institute of Solid Mechanics.

CONCLUSIONS

* referring to the fig. 6 it can observe that the total piezoelectric transducer and adaptation scheme impedance Z1s(r) rise with the acoustic charge r for fundamental frequency. In the case of the new adaptation scheme Z1sa(r) this impedance is more constant than in the case of classical adaptation scheme Z1s(r).

* referring to the fig. 7 it can observe that the total impedance of piezoelectric transducer and adaptation scheme impedance Zs (n) rise with the n harmonic frequency. In the case of the new adaptation scheme Zsa(n) this impedance has a small value therefore at the fundamental frequency the absorbed power is more sizeable.

* referring to the fig. 8 it can observe that the efficiency η1(r) as function of acoustic charge r for fundamental frequency rise with r. This rise is more pronounced at new adaptation scheme.

* referring to the fig. 9 it can observe that the efficiency η(n) as function of n harmonic frequency is littler than the efficiency of the new adaptation scheme. This is the most important advantage of the new adaptation scheme designed and described in this paper. Other advantage of this new adaptation scheme is that the inductance used has a little value therefore it is more easy to built.

It can observe that the impedance "seen" by the generator rises linear, due to the matching dipole, so the power provided by the generator falls with the rise of harmonics number n. The higher harmonics have a small influence on the dissipated power. In this manner the efficiency will grow and all power will be found on the fundamental frequency (n =1).

REFERENCES.

[1] G. Odobescu, I. Rugina – " The efficiency analysis of high ultrasonic systems supplied from electronic generators working in commutation "; the Annual Symposium of the Institute of Solid Mechanics SISOM97, Bucharest, (20-21) November 1997.