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design and simulation of a new controller for resonant operation of piezoelectric ultrasonic tools

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Abstract

Many ultrasonic tools are excited by piezoelectric elements. Most often, resonant vibration is required to achieve maximum energy transformation. Resonance frequency, however, varies when mechanical environment of piezo changes so we need a controller which can tune frequency of driver to resonance frequency. In this paper a voltage resonant inverter is presented which is controlled by a new frequency controller. Conventional frequency controllers are based on PLL theory and tune frequency by using a phase detector and VCO. They change frequency until phase detector output becomes zero. Instead, this controller tends to change the drive frequency so that the reactive component of current approaches to zero and uses S&H and VCO circuit. The system that has been combined with an inverter and so called controller, has been simulated in ORCAD and found very suitable for simulation application because of its simplicity. Also response time of this controller to load change is in the shorter range in compare with conventional PLL controller.

1. INTRODUCTION

Piezoelectric is used in many application related to ultrasonic such as sonochemistry, ultrasonic machining, bonding or cleaning, piezoelectric motors and transformers. In this paper a resonant driver is presented for piezoelectric which is controlled by a new controller that keeps resonant operation in spite of load variations.

Different models for piezoelectric modeling have been used so far [1, 2, 3, 4, 5, 6, 7, 8] and model that has been selected in this study is IEEE model [7]. A full bridge voltage resonant converter is used to drive the piezoelectric with an LC filter to smooth the input voltage. In previous works [9], [10] PLL have been used to control the frequency of driver to keep resonant condition. In this study the controller operates in accordance with elimination the reactive component of the current. The proposed controller has been implemented in ORCAD and simulation results indicate better response with conventional PLL controller.

2. MODELING OF ULTRASONIC ACTUATORS

Many methods for modeling of ultrasonic devices have been presented up to now. Most of these methods are based on substituting the mechanical part by electrical elements. It is very important for electrical engineers that have an electrical model of peizo that can help them to optimize their designs by such models. In this paper an electrical model of piezoelectric used for controller designing. Mason has presented the first model of piezo [1], [2]. He has proposed analytical solution of one-dimensional wave equations using network theory. After that many models have been created by different authors based on his work [3], [4], [5], [6], [7].

The most popular model of piezoelectric is presented by IEEE in [7]. This model, that is shown in figure1.a includes series RLC branch that models mechanical parts in parallel with a capacitor, C_0, that models electrical part of piezoelectric. Following relationships between mechanical parameters and electrical elements have been presented in [8]:

$$L = \frac{M}{T^2}, \quad R = \frac{B}{T^2}, \quad C = \frac{T^2}{K} \qquad (1)$$

M=mass, B=damping, K=stiffness, T=transformer ratio

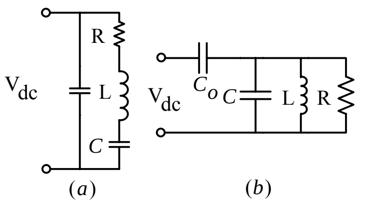


Figure.1: equivalent electrical circuits of piezoelectric. (a)series (b).parallel

In mason model Transformer ratio effect is shown with an ideal transformer but in IEEE model the ideal transformer is eliminated by transferring electrical elements from secondary to primary. In this model current in RLC branch is equivalent to velocity.

As shown in [9] we can consider influence of ultrasonic load damping and stiffness by inserting an equivalent R and C in series with no loading R and C. Another representation of electrical model of piezoelectric is shown in figure1.b that can be easily achieved from circuit theories.

3. FULL BRIDGE SERIES RESONANT INVERTER

Different power electronic circuits have been proposed for driving piezoelectric [10], [11] that many of them are based on resonant inverter. In this paper a full bridge series resonant inverter is used as the driver. Current resonant inverter has been used in many references as mentioned above. But in this type of inverter a current spike appears when voltage is crossing zero. These spikes are due to a little slope deviation from real sinus in voltage wave form. As the capacitor current is equal to $C\, dV_C / dt$, a rapid change will appear in current at each voltage zero cross, where the current waveform distortion causes error in controller operation. To overcome the mentioned problem, voltage source inverter is used here. Figure 2 shows a schematic view of inverter and voltage filter.

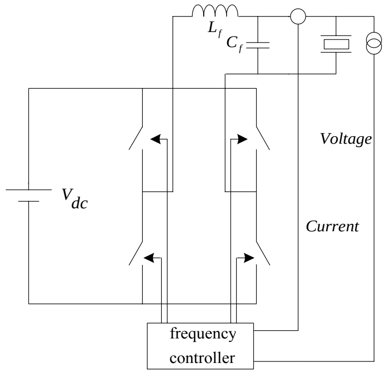


Figure 2. Driver topology used in simulation

As shown in this figure Inverter is fed from an ideal DC voltage source and an LC network is used for inverter output voltage filtering. The capacitor and inductor values must be determined with following conditions:

a) Good quality factor.
b) Minimum input to output current filter ratio.
c) Unity output to input voltage filter ratio.

The following relations can be obtained easily from ac analysis.

$$I_{ratio} = \frac{I_{in}}{I_{out}} = 1 + j\frac{f}{q} \qquad (2)$$

$$V_{ratio} = \frac{V_{out}}{V_{in}} = \frac{1}{1 - f^2 + jfq} \qquad (3)$$

$$q = \sqrt{L_f / C_f} \Big/ R_{Load} \qquad f = \omega / \omega_{resonance}$$

$$\omega_{resonance} = 1 \Big/ \sqrt{L_f C_f}$$

I_{Ratio} and V_{Ratio} plotted versus f for different value of q and q=1 is found suitable in three previous mentioned conditions. Figure 3 shows I_{Ratio} and V_{Ratio} versus f when q=1.

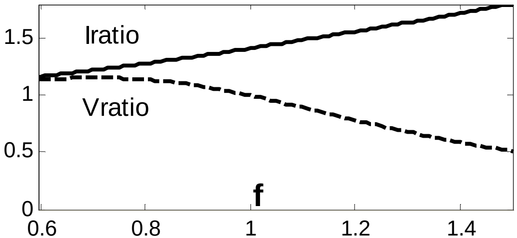


Figure 3. I_{Ratio} and V_{Ratio} versus normalized frequency

According to above mentioned condition the filter components values are chosen as follow:

$$L_f = 30.32\mu H \qquad C_f = 1.89\mu F$$

4. FREQUENCY CONTROLLER CONCEPT

For the chosen equivalent circuit of piezoelectric, there is a series resonance frequency at which maximum energy transformation occurres. At this frequency admittance phase angle is zero. With the load damping and stiffness variation, the piezoelectric resonance frequency would change and a control strategy is necessary to drive the piezoelectric in the new resonance frequency. Two basic ideas for controlled resonant operation are known in ultrasonic technology: The “self oscillating” concept uses the tool itself as a Frequency generator similar to a quartz oscillator: Once being activated (e.g. by means of an on-off switch) the system starts oscillating at its natural frequency. For compensation of damping, the oscillation gets amplified and is sent back to the vibrator in a positive feedback-loop. It is pleasantly easy to implement this concept in practice but it shows several disadvantages regarding robustness in presence of strongly variable loads [13].

The second concept is the “phase-locked loop” concept (PLL) which has been adopted from communications engineering where it finds application for synchronization of two electrical signals. The basic idea of a phase controller is as follows: if the phase between current and voltage (e.g. at the piezoelectric actuator) is positive, the driving frequency is increased, otherwise decreased. The main difference compared to the self oscillating concept is that the driving frequency is excited by an external frequency generator. In PLL method a phase detector is used to determine phase difference between voltage and current of piezoelectric actuator; then phase difference is transmitted to a VCO and VCO produce a periodic signal that its frequency changing is proportional with phase difference. Proportional gain is linear approximation of no load admittance phase diagram of piezoelectric. Figure 4 show graphical illustration of this concept.

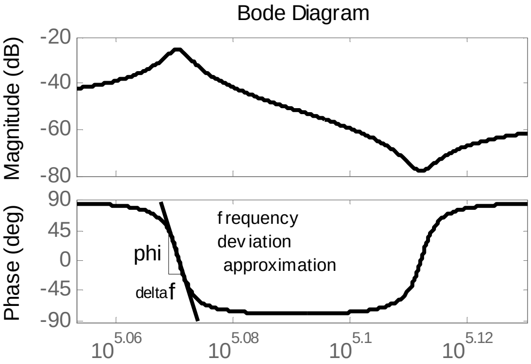


Figure 4. Linear approximation of phase admittance diagram

The controller which is presented here uses a value that is proportional to phase difference between voltage and current of piezoelectric and is an approximate measure of real phase difference. This value is reactive component of current that becomes zero when resonance occurs. Sampling reactive component of current is easier than measuring phase difference, there for, implementation of this controller is easier than conventional PLL controller.

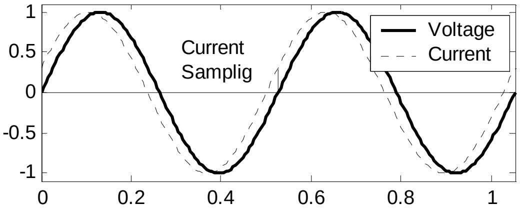


Figure 5. Current sampling idea

The controller samples current at voltage zero crossing , as shown in figure 5, by using a sample and hold and then a VCO uses this sampling data for frequency tuning.

Relation between sampled current values and phase difference can be shown as follow:

$$\begin{cases} I = I_0 \sin(\omega t + \varphi) \\ \omega t = 0 \end{cases} \Rightarrow I = I_0 \sin(\varphi) \xrightarrow{\varphi<30}$$

$$I \approx I_0 \times \varphi \qquad (4)$$

An integrator is used in order to have zero steady state error.

For determining the integrator gain, relation between frequency and phase is obtained and then linearized at no load resonance frequency. This linearized quantity is used for controller designing. The following procedure shows linearization method.

$$|\varphi| \le 30 \to \varphi = \left(\frac{1}{RC_O} - \frac{R}{L} - \frac{2RC}{LC_O}\right)\frac{1}{\omega} + \left(\frac{RC^2}{C_O} + RC\right)\omega + \left(\frac{R}{L^2 C_O}\right)\frac{1}{\omega^3} \qquad (5)$$

$$\to \varphi = \varphi(\omega_{resonance}) + \frac{\partial\varphi}{\partial\omega}\bigg|_{\omega_{resonance}} \left(\omega - \omega_{resonance}\right) \qquad (6)$$

Graphical interpretation of (6) can be seen in figure 4.

5. FREQUENCY CONTROLLER IMPLIMENTATION IN ORCAD

Controller circuit as shown in figure 6 is made of seven parts. Current is measured by transformer and then sampled with S&H unit. S&H shows reactive current of piezoelectric. Comparator produces a square wave that is in phase with voltage waveform. Output signal of the comparator excites a monostable. Monostable is set to be triggered by positive edge of comparator signal and generate a pulse with 1 μs width. monostable output opens and closes an analog switch so sample and hold unit can sample current signal and save it in a capacitor. The next unit is integrator that acts as stated in previous section. VCO is fed by integrator and generates a sinusoidal voltage whose frequency is determined according to following model:

E^@REFDES %OUT 0 VALUE {SIN (6.28*TIME*(F_O+V (%IN)))} (7)

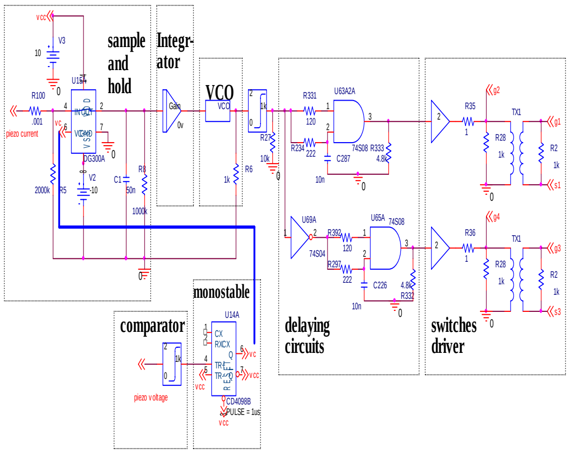


Figure 6.frequency controller circuit in simulation

F_0 is VCO central frequency. A comparator is used to convert the sinusoidal output of the VCO into a square wave which is applied to the inverter drive unit. Also a dead time is introduced to avoid shoot-through problem in the inverter. The last part is driving circuit which provides the required voltage or current for the main switches of the inverter. Two transformers are used in this part for the upper switches which have different ground voltage than the common ground of the circuit.

6. SIMULATION RESULTS

A piezoelectric resonator with the specifications presented in table 1 and derived as stated in the previous sections is simulated by ORCAD.

Table 1. Piezoelectric equivalent circuit elements value

Piezo characteristics	No load	Full load
Resonance frequency(Hz)	18900	18525
R (Ω)	4.59	57.573
L (mH)	17.534	19.368
C (nF)	4.045	3.802
C_o (nF)	18.006	18.783

Simulation results show ability of the controller to tune the frequency within a reasonable time when the system is started from rest or load is changed from a previously tuned condition. Figure 7 shows the reactive component of current which is recorded by S&H unit at start up with full load concerning to the parameter values stated in table 1. It indicates that the system goes into resonance within about 80ms. In figures 8-a and 8-b during and after start up respectively. Now a sudden change in load, from the previous condition to a new condition with R=50Ω, C=3.7nF, L=18.53mH and Co=18.783nF is applied. The results are presented in figures 9 and 10. As these figures indicate, current amplitude decreases substantially due to detuning of the driver from the new situation's resonance frequency and then increases again, as the controller reacts and tunes the switching frequency to the new resonance condition. Response speed of the system depends on factors such as load damping and central frequency of VCO as well as the other parameters and controller gain. Through various simulations, response time between 20ms and 100ms was obtained, which is better, or at least, in the range reported in previous publications such as [16], while a relatively simpler controller has been used in this study.

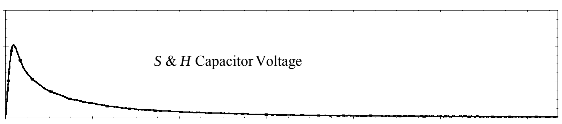
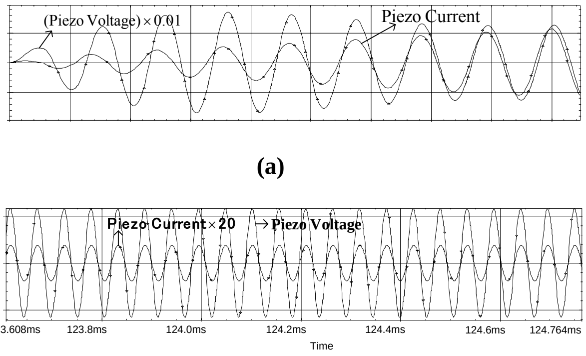


Figure7. S&H signal at start up with full load



(a)

(b)

Figure 8. Current and voltage of piezoelectric: (a) during start up (b) at steady state

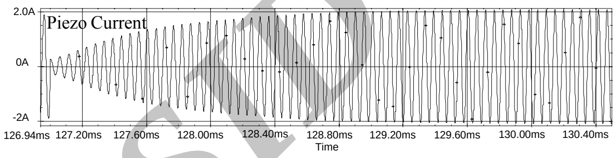


Figure 9. piezo current variations when a load change is applied

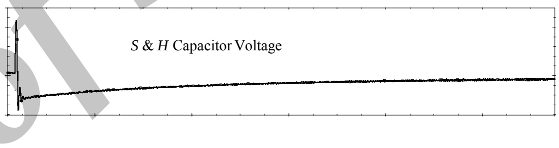


Figure 10. S&H signal when a load change is applied

7. CONCLUSION

A new controller was presented for frequency tuning of the driver of piezoelectric devices and its performance was examined by simulation. IEEE model was selected for piezoelectric and a full bridge voltage source inverter, with an LC filter in the output, was used to drive the system.

The controller implemented in this study is based on measurement of reactive component of piezoelectric current witch is easier than the conventional PLL method. Despite of simplicity of the controller, the results obtained by the presented controller were found the same and even better than those reported in previous studies.

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