Modular Test Equipment for Analysis and Operation of Ultrasonic Motors

Introduction

The movement of ultrasonic motors is based on the transfer of vibration energy from a mechanical resonator to a suitably guided surface over frictional contact, Fig. 1.

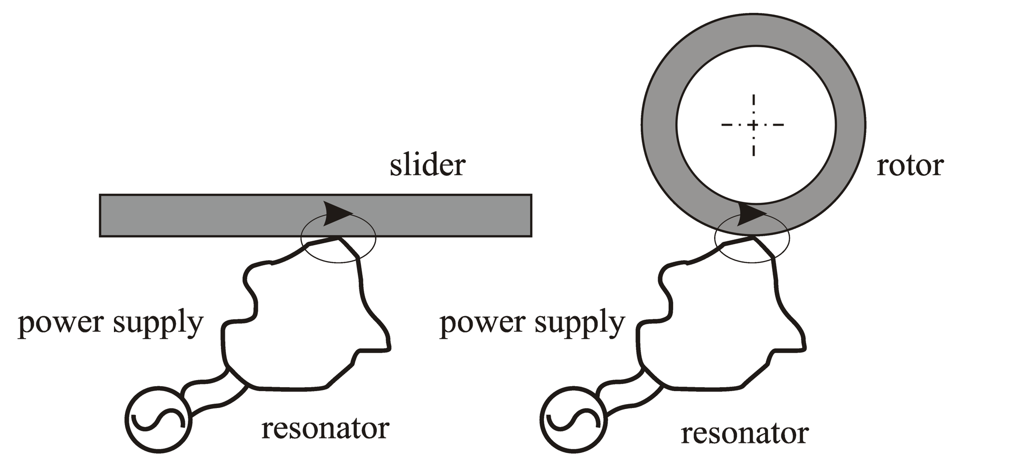

Fig. 1: Stator Vibrator

The vibration is excited at frequencies in the ultrasonic range (>20 kHz) using the inverse piezoelectric effect (1) that describes the generation of mechanical strain S from a mechanical stress T and an applied electric field E. The effect is reversible (2) and can be used equally to generate dielectric displacement D and electrical energy from mechanical stress.

$$S = s_E \cdot T + d^t \cdot E \quad (1)$$

$$D = d \cdot T + \varepsilon_T \cdot E \quad (2)$$

Ultrasonic motors operate silently due to their high excitation frequency and show some special characteristics that in certain cases offer advantages over conventional actuators, e.g. a high holding force in the power off state.

Driving Ultrasonic Motors

Requirements for the excitation of single and multiple phase piezoelectric resonators cannot be met with standard equipment. The availability of amplifiers to drive piezoelectric loads is limited and only a few manufacturers are able to deliver appropriate devices to drive high power ultrasonic resonators. However, these amplifiers usually operate from a source signal generated with function generators. As these standalone devices in most cases have GPIB connectors some basic functional tests using LABVIEW are possible but this is about the limit of performance evaluation that can be implemented. A really flexible workstation must be faster in order to implement feedback control and must be capable to drive single and multiple phase resonators, especially as the latter offer distinct advantages with respect to their controllability. For laboratory use DSP based prototype controller boards like those offered from DSPACE which interface Matlab/Simulink as a powerful tool for control system design are an attractive approach for different applications. However due to the high excitation frequencies direct excitation signal generation is not feasible. The analogue outputs of a fast DS1103 prototype board can be operated only up to 20 kHz with sufficient signal quality, but this is just where ultrasonic motors start to operate. Another major drawback of this controller board based signal generation is, that computing power is consumed for low level tasks. Thus it is necessary to design circuits that can perform the signal generation and free computing power of the DSP board upon which the prototype control system will be based.

Control System Design

Fast excitation signal generation is crucial to realize a prototype control system. Fig. 2 shows the structure of a device built on direct digital synthesis (DDS) based numerical controlled oscillators (NCO) that allow programming of sine wave and triangle wave output signals at any desired phase shift to drive multiple phase ultrasonic resonators.

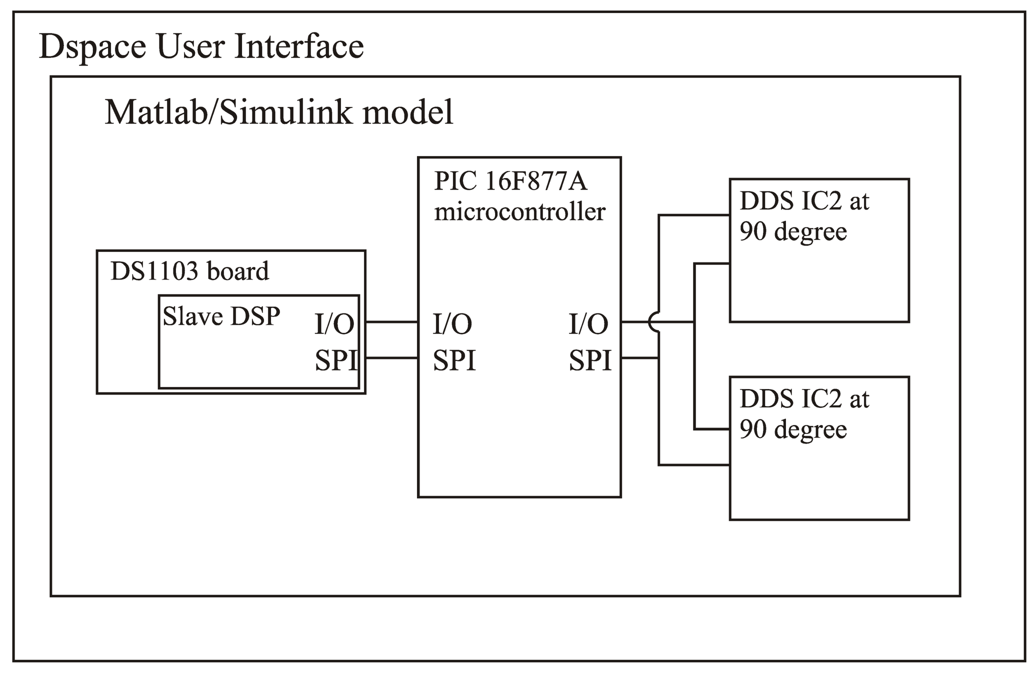

Fig. 2: Communication strategy

The DSPACE interface is used to transfer operator input to a MATLAB/Simulink model that runs on the controller board and controls a microcontroller used to implement two different circuits with phase shifted outputs. The first circuit generates two 90 degrees phase shifted sine waves at frequencies up to 120 kHz and is used to drive four quadrant amplifiers. The second circuit operates two 90 degrees phase shifted full bridge inverters with pulse width modulation and can be driven at frequencies up to 300 kHz. Fast changes from phase lead to phase lag of one phase with respect to the other can be achieved due to a phase reversal based on fast logic gate circuits without the need to reprogram the NCO phase registers.

Sine Wave Generator

The sine wave output of the used DDS IC (AD9833) is unipolar with only 0.6 V and is not suited to drive the four quadrant amplifiers that need a 10 $V_{p\text{-}p}$ input signal for full output swing. The signal level needs to be amplified, level shifted and of course amplitude control needs to be implemented. Fig. 3 shows a schematic circuit diagram.

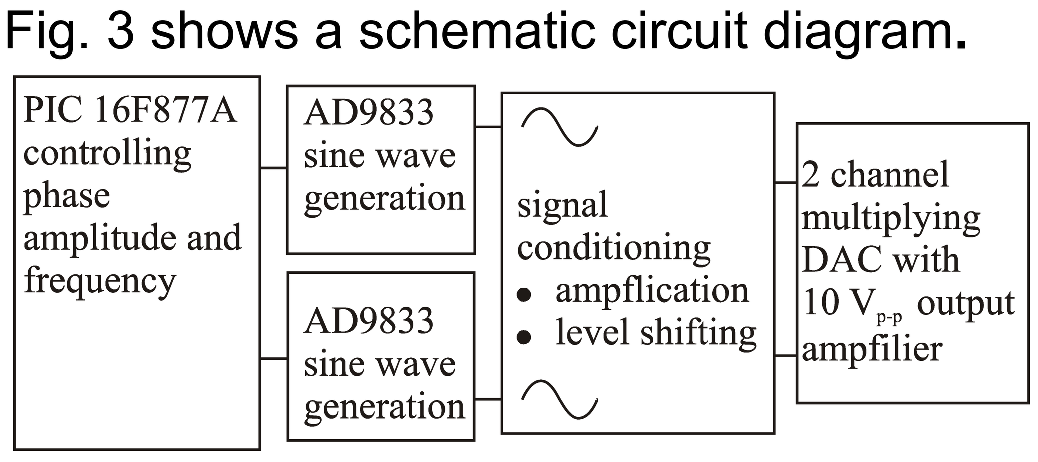

Fig. 3: Sine wave generator schematic

The microcontroller sets the output frequency of the NCO. The low voltage output is conditioned using operational amplifiers and finally digital amplitude control is achieved with a multiplying digital-analog converter (DAC) from Analog Devices (AD7837). The reprogramming for a new amplitude is completed in 500 µs. Phase reversal for direction changes can be performed even faster as the NCO offers two phase registers that can be programmed with different content and addressed by reprogramming the status register of the NCO. Fig. 4 shows the first working prototype built in the lab.

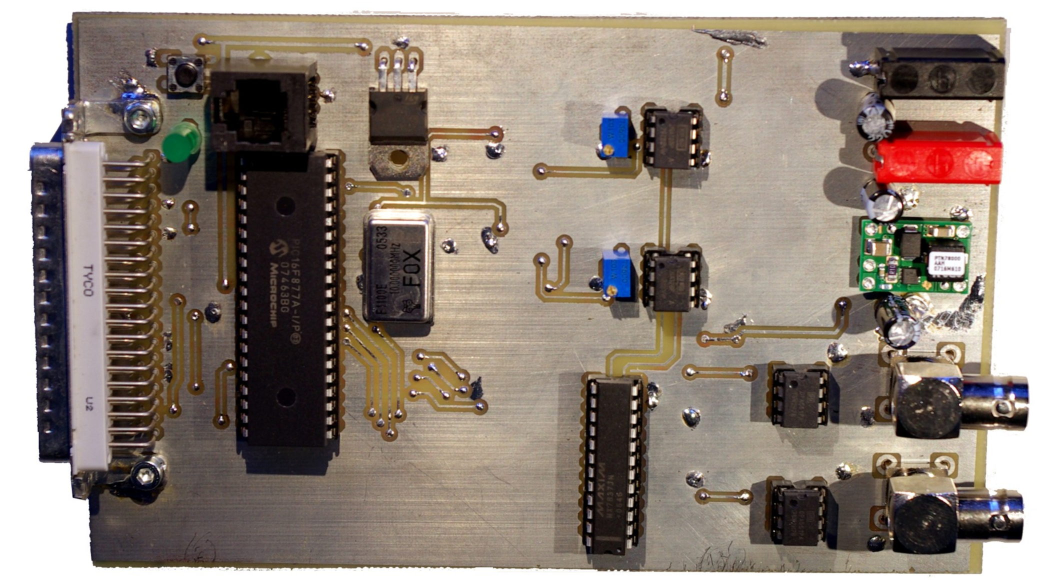

Fig. 4: Prototype sine wave generator

Square Wave Generator

Square wave inverters with output filters are the industrial standard excitation devices for ultrasonic motors. They are built as full bridge or half bridge push-pull inverter circuits that can be controlled using pulse width modulation. Unlike conventional amplifiers switched inverters can be miniaturized easily and are less expensive to produce. Fig. 5 shows the schematic diagram of the developed dual phase inverter with +/-90 degrees phase shift.

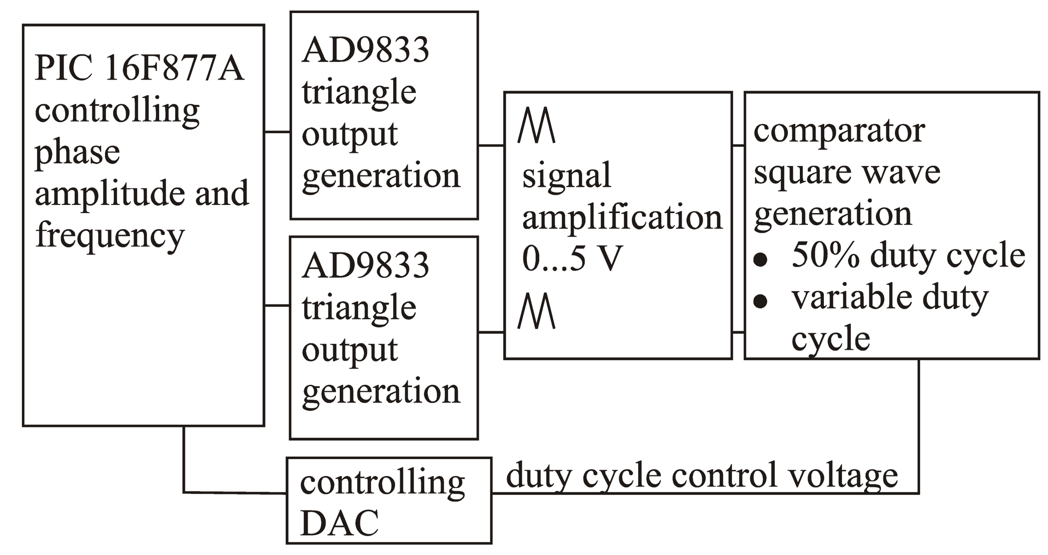

Fig.5: Square wave generator schematic

The resonator uses one vibration mode to create movement and the second vibration mode to create normal force on the frictional contact. As the normal force should be high one phase of the inverter is operated at a duty cycle of 50 %. The second phase is operated with a variable duty cycle to control the motor speed. Fig. 6 shows the prototype of the printed circuit board with no filter components attached.

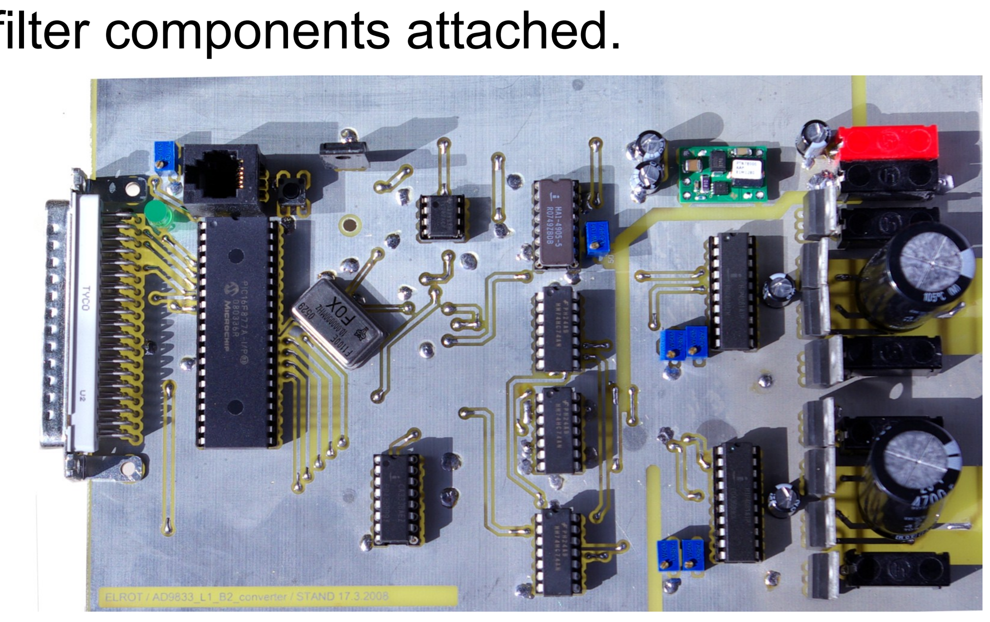

Fig. 6: Prototype square wave inverter

Conclusion

Using the presented circuits a DS1103 controller board can be used to control a variety of single and multiple phase ultrasonic motors. Two different circuits have been demonstrated that can be operated with four quadrant amplifiers or a switched inverter and drive motors at frequencies up to 300 kHz.

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