Signal Processing for Single Transducer Distance Measurement Applications to Reduce the Blind Zone

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Abstract

Piezoelectric air ultrasound transducers typically have a small bandwidth. So they cannot be used to transmit short signals. This leads to a blind zone which prevents measuring short distances in single transducer applications, because normally receiving is not possible until transmitting is finished. The blind zone is significantly increased if coded signals are used which is necessary to identify different sensors in a multi sensor environment to reduce crosstalk. One solution is to implement a simultaneous transmitting and receiving operation by model based suppression of the transmitted signal. It is possible to measure distances down to 50 mm using fixed signal processing. To measure smaller distances the signal processing has to be modified. This contribution shows an extended signal processing for further reduction of the blind zone.

Key words: Blind zone, simultaneous, ultrasound, distance measurement

Introduction

Most industrial ultrasound distance sensors use only one transducer for transmitting and receiving. Thereby it is normally not possible to detect any acoustic echo during transmitting and transient oscillations. This leads to a blind zone for distance measurement applications. The length of the blind zone depends on the length of the transmitted signal and on the bandwidth of the used transducer. Piezo-electric air ultrasound transducers normally have a small bandwidth which leads to longer transient oscillations. This defines the smallest distance to be measured for single transducer applications. To prevent cross talk in multi sensor applications, the transmitted signal could be coded to identify echoes of different sensors. The drawback of coded signals is the significant increase of the blind zone due to the required length of the transmitted signal. This problem can be solved with a simultaneous transmit and receive operation. There are several approaches using an analog sensor interface for the realization [1, 2, 3]. The drawback of those realizations is that they are suitable in steady state only which is a problem when coded signals are used with narrow band transducer. A solution is to use digital signal processing to estimate the electrical received signal using higher order models as shown in [4, 5]. Thereby common air ultrasound transducer with a small bandwidth can be used.

Concept

The main idea for digital signal processing based approaches is to drive the transducer via a series resistor R_S. Then the transducer signal u_T consists of one part generated by a generator u_{TG} and the electrical received signal u_R. This basic circuit is shown in Fig. 1.
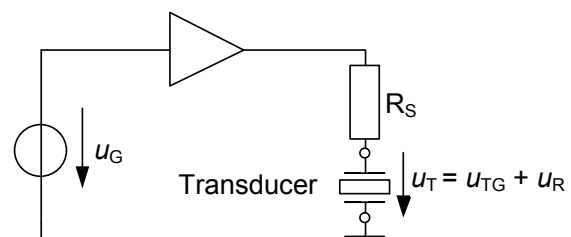

Fig. 1: Transducer driven by series resistor

To calculate the electrical received signal from a measurement of the transducer signal u_T and the generator signal u_G a mathematical model of the behavior of the circuit is necessary. Due to the influence of temperature, acoustic load and aging to the transducer, the model is time variant and cannot be fixed. It has to be estimated online. This is the critical point of the concept because the estimation using a single measurement has a small minimal reflector distance too. Below this distance the uncertainty of the estimated model parameters

is quite high and the model should not be used for distance measurement. One solution to increase the reliability of the model parameters for small reflector distances is averaging of several measurements with different reflector positions [5]. After the model parameter estimation the electrical received signal can be calculated as the difference of the measured transducer signal and the model signal.

Averaging cannot be used for the whole measurement range because the trigger jitter of the measurement system leads to varying dead times in the averaged signals. This generates a small time offset between the model signal and the measurement to be processed, which reduces the suppression of the transmitted signal. Thereby it cannot be used for higher reflector distances with small echo amplitudes. An adaptive signal selection (averaged signal, single measurement) is introduced to improve the model identification. It uses a rough distance estimation done by a former signal analysis.

Signal analysis

To select a suitable preprocessing for the model parameter estimation a rough estimation of the echo/reflector distance is necessary. For the proposed signal processing it is sufficient to distinguish far echoes (distance greater than 100 mm) from near echoes. So the goal of the first signal analysis is to calculate a scalar value depending on the echo distance. For the examples shown in this chapter an air ultrasound transducer (400SR160 Pro-wave Electronics Corp.) is used.
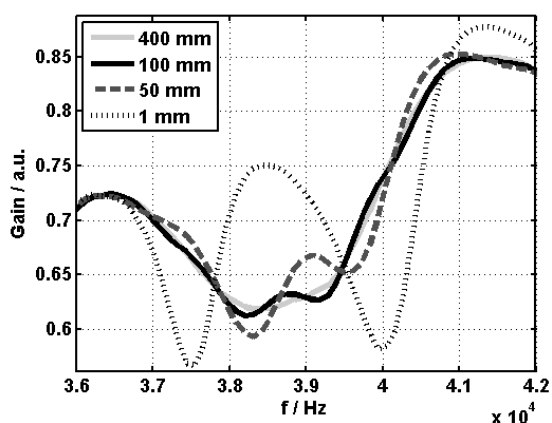

Fig. 2: Influence of an echo on the gain response for different reflector distances

One indicator can be calculated from the gain response of the electrical system which is calculated from the generator signal and the transducer signal in the frequency domain for this example. An electrical received signal

leads to an additional resonance in the frequency response, depending on the amplitude and dead time (echo distance) as shown in Fig. 2.
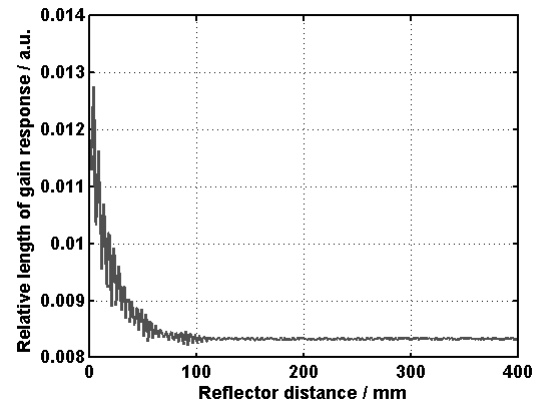

Fig. 3: Relative length of the gain response around the center frequency of the transducer depending on the reflector distance

There are several ways to calculate a scalar value from the gain response which deliver similar results. To keep the complexity of the signal analysis as small as possible, the relative length of the gain response around the center frequency of the transducer is calculated. This leads to the graph shown in Fig. 3. Using this feature it is possible to identify close echoes in a small area up to 25 mm reflector distance.
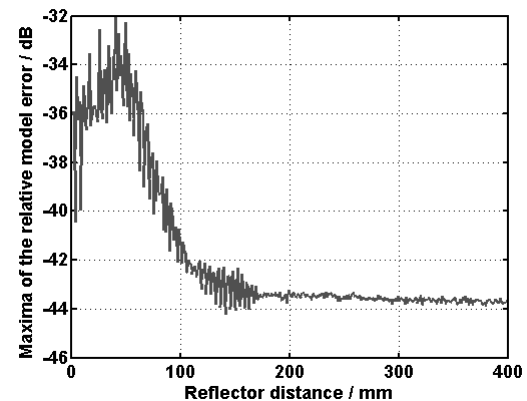

Fig. 4: Relative model error depending on the reflector distance

Another way to estimate the rough reflector distance is to perform a model parameter estimation using the transducer signal and generator signal of the whole transmitted sequence. Then the error of the estimated model can be used as a feature. Here it is defined as the maximum of the difference between the measured transducer signal and the model output signal. To calculate the relative model error it is referenced to the maxima of the transducer signal.

If there is an echo in the transducer signal, the model error will increase because the echo cannot be reproduced by the model without errors. So the model error depends on the reflector distance even if the model is not correct, as shown in Fig. 4.

For further evaluation a threshold is used to determine if the echo is near or far. Considering the model error criterion the threshold could be about -40 dB for the example shown in Fig. 4. The relative model error shows smaller values for reflector distances below 15 mm. This area has a high uncertainty for the rough estimation of the echo distance. Nevertheless by considering both features a stable estimation algorithm is implemented.

Preprocessing

The preprocessing consists of two modules. At first, a jitter reduction algorithm based on [6] is used. It reduces the influence of the trigger jitter of the used measurement system on both, the generator and the transducer signal. This is necessary because the trigger jitter leads to a varying dead time of the averaged signals compared to the single measurement. Thereby the suppression of the transmitted signal is reduced significantly. Then it is impossible to detect any echo due to the relative small

amplitude of the electrical received signal compared to the generator signal.

The reference for the calculation of the signal shift by the trigger jitter is the averaged signal itself. To eliminate the influence of an echo to the estimation of the trigger jitter, the estimation is done on band pass filtered signals above the acoustic relevant frequency spectrum. Both, the calculation of the shift between the reference and the measured signal and the correction are done in the time domain [6]. Finally an exponential filter generates the averaged signals.

The second module is used for the transducer signal only. It is a band pass filter to reduce the influence of resonances which are not relevant for the acoustic operation. So the model order can be reduced even though the band pass filter has to be modeled too.

The preprocessing block generates four signals of the transducer and generator signal. A band pass filtered transducer signal u_{TF}, a band pass filtered and averaged transducer signal u_{TA}, a generator signal u_G and an averaged generator signal u_{GA}.
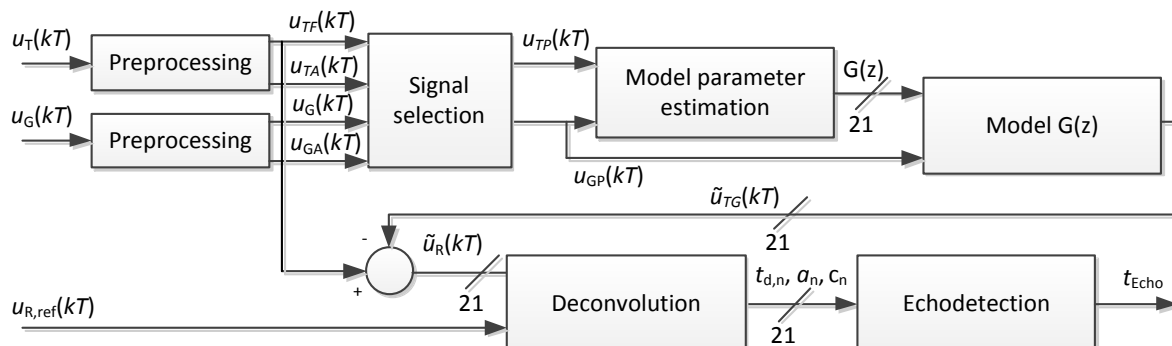

Fig. 5: Signal processing scheme of the presented distance measurement system

Signal processing

The signal processing consists of different modules as shown in Fig. 5. After the preprocessing the transducer signal is analyzed to determine whether the echo is near or far (/without echo) using the features described in the chapter "signal analysis". Depending on the result of the transducer signal analysis the signals for the model identification are selected. If the echo is estimated to be far, the actual measurement (u_{TF} and u_G) is used for the model parameter estimation. Otherwise the averaged signals (u_{TA} and u_{GA}) are used. If the

system is powered on and there are no averaged signals, it uses the single measurement for the first model parameter estimation.

For the model parameter estimation a StMcB algorithm [7] is used. To increase the reliability of the echo estimation, the model estimation is performed for a number of sections (21 in this example) with different length of the input signals. Thereby the sections start with the first sample and only the ends vary [5]. These model parameters are used to estimate the electrical transmitted signal $\tilde{u}_{TG}$. This is done with an IIR filter. Using each model signal an estimated electrical received signal $\tilde{u}_R$ is

calculated by subtracting the model signal $\tilde{u}_{TG}$ from the preprocessed transducer signal u_{TF}. Thereby a cluster of different electrical received signals is estimated.

The calculation of the time of flight of an echo is splitted in two blocks as presented in [5]. First a deconvolution of the estimated electrical received signal $\tilde{u}_R$ with a fixed reference signal $u_{R,ref}$ is calculated. This leads to the time of flight $t_{d,n}$, the amplitude a_n and the correlation coefficient c_n for the n first echoes for each electrical received signal of the cluster. These features are analyzed in a second step to separate real echoes from phantom echoes caused by model errors. First the amplitude a_n of a possible echo is used to filter too small echoes. Then the correlation coefficient c_n is evaluated. The idea is that the position of a real echo is independent of the model and should have similar times of flight for different models. So the absolute frequency of a certain time of flight in the cluster is one feature for the probability that an echo is real. This is evaluated by summing the correlation coefficients of the cluster with the same time of flight. Due to the non-optimal suppression of the transmitted signal, there is a small variation in the calculated time of flight for identical echoes. Thereby neighbors are summed using a moving average filter. Afterwards the time of flight with the highest summarized correlation coefficient is supposed to be a real echo.

Experimental Setup

The presented signal processing is verified using a 40 kHz air ultrasound transducer with a bandwidth of 2.5 kHz (400SR160 from Pro-wave Electronics Corp). It is driven by an operational amplifier (THS6012). Data acquisition and transmit signal generation is done by an USB oscilloscope with an integrated generator. Its resolution is 14 bit at a sampling frequency of 1.5625 MHz. The transducer is mounted on a computer controlled linear unit as shown in Fig. 6. It is faced orthogonal to a quadratic metal reflector (100 mm x 100 mm). The whole measurement setup is controlled by MATLAB®.
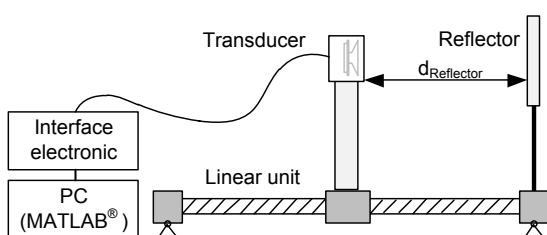

Fig. 6: Simplified experimental setup

For these measurements a BPSK modulated transmit signal with 40 kHz carrier and 4 cycles per symbol is used. It transmits a 31 bit gold code. The signal length in air is about 1200 mm. Therefore a separation of the transmitted and received signal for reflector distances up to 600 mm is necessary. For higher distances the signals are already separated. This defines the range for the experimental verification. Thereby one measurement run consists of 600 single measurements with increasing reflector distances from 1 mm up to 600 mm in steps of 1 mm.

The signal processing is done offline after the measurement run is finished. Thereby the order of the single measurements is randomized to simulate different objects to be detected like in the practical application of the sensor.

Results

The results are subdivided in two parts. First the calculated reflector distances without adaptive signal selection are shown for comparison.
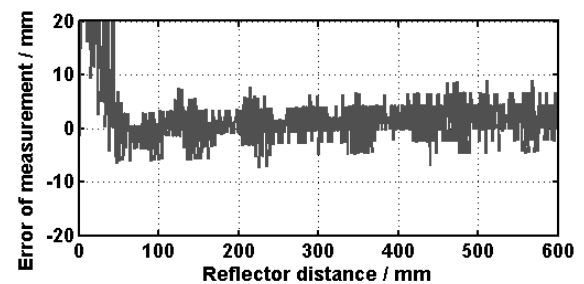

Fig. 7: Absolute error of measurement for single measurement processing

The single measurement processing as shown in Fig. 7 is capable to detect echoes starting at a reflector distance of 50 mm. Closer echoes cannot be detected due to limits of the system identification algorithm. For closer distances averaging of the measurement signal is necessary to reduce the influence of the echo to the system identification.
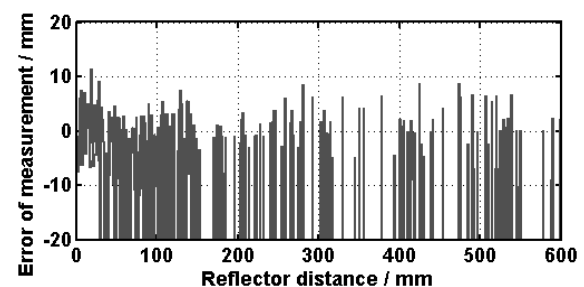
Fig. 8: Absolute error of measurement for processing using averaged signals without jitter correction

Fig. 8 shows the results using averaging of the ascending measurements but without trigger jitter correction. The influence of the trigger jitter reduces the model quality, so it is impossible to detect echoes above 30 mm reflector distance. When a jitter reduction algorithm is used, the detection of echoes with higher reflector distances is possible as shown in Fig. 9.
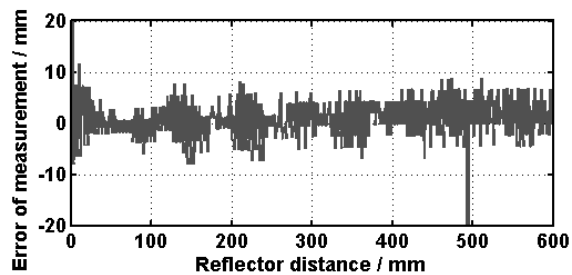

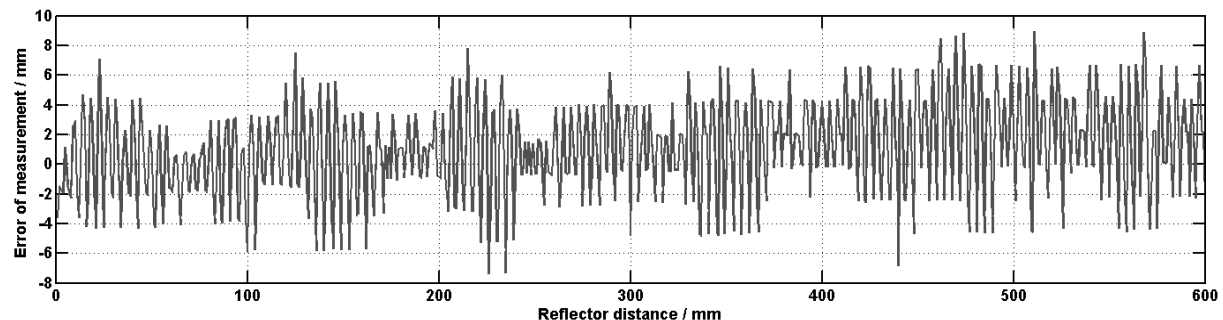*Fig. 9: Absolute error of measurement for processing using averaged signals with jitter correction*

For the second measurement the averaging already works fine. The results for higher reflector distances show some spikes caused by minor trigger jitter. Other spikes can occur at small distances depending on the history of the averaged signals.

If the adaptive signal selection is used the errors of measurement for small reflector distances are reduced as shown in Fig. 10. Depending on the order of incoming measurements (history of the averaged signals) single errors in the distance measurement can occur for small distances below 100 mm. The absolute error of measurement is smaller than the wavelength of the ultrasound signal (about 8.5 mm). A closer look shows a periodicity of the error of measurement which is exactly half the wavelength of the transmitted signal. It is caused by the unsuppressed part of the generator signal which is correlated to the received electrical signal. The summation leads to a phase shift of the resulting signal and a time shift in the correlation function used for the distance calculation.

Fig. 10: Absolute error of measurement for processing adaptive signal selection

Conclusion and outlook

The shown signal processing enables ultrasound distance measurements without blind zone. The algorithm works especially for modulated, coded transmitted signals like the BPSK modulated signal used for the experiments. In the experiments the system is able to measure distances up to 600 mm. Higher distances can be measured without the shown algorithm using classic transmit/receive switches and receive signal amplifiers. The used single measurement processing which is limited down to 50 mm reflector distances is extended by a signal processing using averaged signals to measure smaller distances down to 0 mm. Thereby the experiments show an distinct influence of the trigger jitter of the used data

acquisition system which prevents measurements above 30 mm reflector distance using averaging. To solve this problem a jitter correction is implemented. It improves the signal and model quality using averaged signals so that measurements from 0 mm up to 600 mm reflector distance are possible.

In further work the averaging algorithm has to be improved to overcome the problem of measuring fixed small distances. Here the averaging will decrease the model quality because the echo signal is constant and won't decrease by averaging. To prevent this, the measured distance could be used to stop averaging if the reflector distance is unchanged.

The final step is an optimization of the algorithm to reduce the required computational time. This

can be done by reducing the signal length using base band signals. Later the system can be implemented on embedded hardware using a DSP or microcontroller.

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