INVERSE FILTER TECHNIQUE FOR HIGH-PRECISION ULTRASONIC PULSED WAVE RANGE DOPPLER SENSORS

H. Ruser, M. Vossiek, A. v.Jena, V. Mágori
Corporate Research and Development, Siemens AG, 81730 München, Germany

ABSTRACT

Ultrasonic pulsed wave range Doppler sensors provide application in various fields, e.g. intruder alarm systems or autonomous vehicle steering, [1], [2], [3]. The time-frequency methods [4, 5] commonly used in these sensors, however, inhere the problem that, due to the transducer's non constant and direction-dependent transfer functions, the Doppler frequency cannot be determined with high accuracy needed for such applications. The easiest way to improve the Doppler resolution is to reduce the signal bandwidth, but only at the expense of worse range resolution. In this paper a direction-dependent inverse filter technique is presented, which compensates erroneous effects of the transfer function in the time-frequency analysis. An ultrasonic intruder alarm system determining location and velocity of persons in rooms serves as an example that the novel approach gives evidently better performance than conventional methods, resulting in both high velocity and range resolution.

INTRODUCTION

To localize *N* objects in a multi-object scene, a theoretical number of *N+1* independent wide-angle receivers is needed. The targets are detected by threshold evaluation of the signal envelope of each receiver. A time-frequency analysis is performed separately for each echo. This includes echo time measuring to obtain the range information as well as short time FFT for the specific echo window to determine the Doppler shift and by this the target's velocity. This simple method, however, inherits large errors especially for the velocity measurement: If the transfer function is not constant over the entire evaluated frequency range, an effect of frequency shifting is observed, cf. Fig. 1, which is added to the Doppler frequency shift. A possible way to minimize this effect is to choose a small frequency band with a roughly linear transfer function, what, however, causes a reduced range resolution. Hence to enable high precision measurements of range and velocity for objects with unknown location in a room, a compensation for the transfer function in each direction to the receiver is needed.

NOVEL INVERSE FILTER TECHNIQUE FOR DIRECTION-DEPENDENT COMPENSATION OF THE TRANSFER FUNCTION

In a typical ultrasonic pulse-echo measurement system the transducer is stimulated with the burst signal $s(t) = rect\left(\frac{2t-T}{T}\right)cos(2\pi f_0 t)$ of frequency f_0 and duration *T*. An acoustic wave is emitted into the medium and reflected to the receiver from objects in front of the transducer. In frequency domain, the received signal can be described as the time-delayed replica of the transmitted pulse multiplied with the overall system's transfer function $H(\omega,\psi,r)$.

For a target in direction ψ and distance r $H(\omega,\psi,r)$ can be expressed as:

$$H(\omega,\psi,r) = B(\omega,\psi)\cdot A(\omega,r)\cdot R(\omega,\psi)\,, \qquad (1)$$

where $B(\omega,\psi)$ is the radiation pattern function resulting from the radiation patterns $B_t(\omega,\psi)$ and $B_r(\omega,\psi)$ of the transmitter and receiver for the interesting frequency range, resp. $A(\omega,r)$ describes the

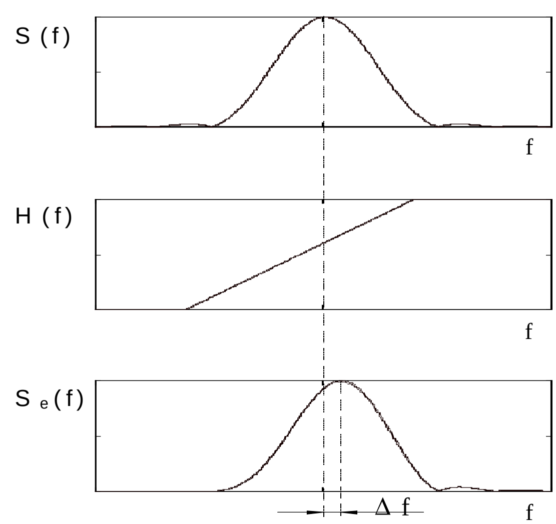

Fig.1: Frequency shift due to a nonlinear transfer function
S(f) - signal spectrum, H(f) -transfer function,
S_e(f) - shifted spectrum, Δf - frequency shift

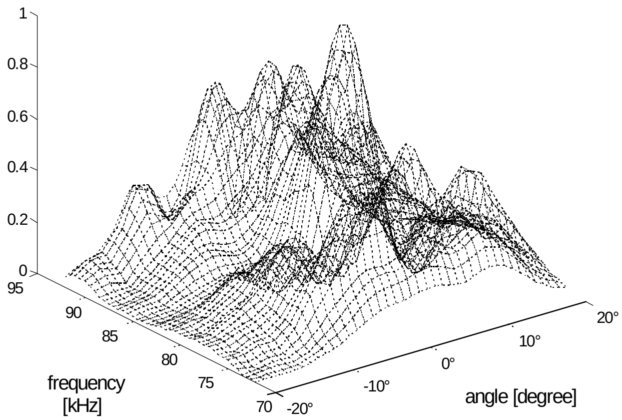

Fig.2: Direction-dependent directivity $B(\omega,\psi)$ pattern of a RU ultrasonic transducer

transmission loss for target range r and $R(\omega,\psi)$ the characteristic of the reflector. For the reflection of air-borne ultrasound at large objects, $R(\omega,\psi)$ can be assumed to be constant [3] and $A(\omega,r)$ is determined numerically with an absorption coefficient α (α can be expressed by the approximation $\alpha \approx f\,[Hz]^2 \cdot 1{,}5 \cdot 10^{-11} s^2 m^{-1}$, [3]):

$$A(\omega,r) = \frac{1}{r^2} exp(-\alpha r) \qquad (2)$$

Hence, to determine $H(\omega,\psi,r)$, the radiation pattern $B(\omega,\psi)$ has to be measured for the interesting frequency range. An example of the radiation pattern of a ultrasonic transducer suitable for pulsed-wave measurements in air, measured in free-field conditions, is given in Fig. 2 [7]. Another approach is to determine $H(\omega,\psi,r)$ form the ratio of the spectra of the received and the transmitted pulse:

$$H(\omega,\psi,r) = \frac{E(\omega,\psi,r)}{S(\omega,\psi,r)} \qquad (3)$$

A common tool for compensating the transfer function of the measuring system is to filter the received signal with the inverse of the transfer function. For optimal noise reduction, the inverse filter is combined with a noise filter. This combination, which offers minimal signal distortion and maximal reduction of noise, is the Wiener filter. The noise filter is given by the ratio of the power spectrum of the signal and the sum of the power spectra of the signal and the noise. With the signal power spectrum estimated by the amplitude spectrum of the direction-dependent transfer function $H(\omega,\psi,r)$ and its complex conjugate $H^*(\omega,\psi,r)$, the time-frequency characteristic of the Wiener filter $I(\omega,\psi,r)$, selected for the interesting frequency range by the window function $W(\omega)$, can be calculated from [6,7]:

$$I(\omega,\psi,r) = \frac{H^*(\omega,\psi,r) \cdot W(\omega)}{H(\omega,\psi,r) \cdot H^*(\omega,\psi,r) + \phi_s / \phi_n} \qquad (4)$$

ϕ_s and ϕ_n are the power spectrum density of the signal and the noise, respectively. If the signal-to-noise ratio is high, the filter tends to a pure deconvolution filter, in case the signal-to-noise ratio is low, it represents a matched filter. Here, it is assumed, that for the selected frequency range the ratio ϕ_s / ϕ_n is constant for all directions and frequencies.

The steps in Wiener filtering for a certain direction ψ_0 are shown in Fig. 3. The time and frequency response of the reflector signal are shown in Fig. 3 a) and b) resp. Fig. 3 c) shows the transfer function of the Wiener filter. In Fig. 3 d) the filtered echo spectrum is presented. For an ideal match, the output signal equals the window function.

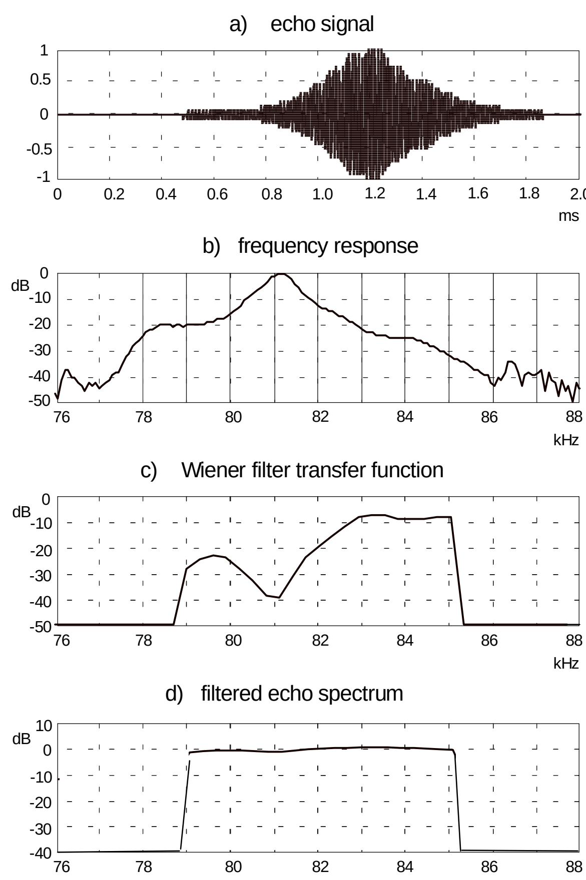

Fig.3: Wiener filter echo evaluation

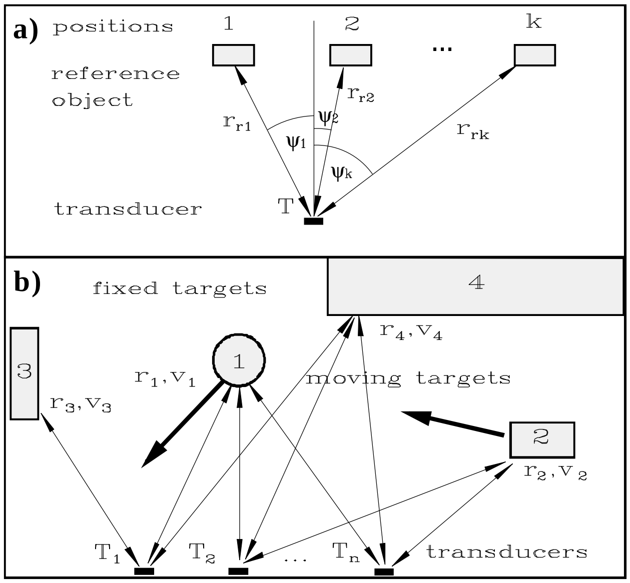

Fig. 4: Signal evaluation in two steps
a) setup: determination of direction-dependent inverse filters with reference reflector
b) measurement: multi-object scene with n transducers

MEASUREMENTS

In order to verify the ability to compensate the erroneous frequency shift for high precision measurement of range and velocity of objects, tests were carried out in a closed room with a ultrasonic pulse echo system. The principle of measurement using *n* transmitter/ receiver pairs (in our case $n = 3$) placed in the observation room, is sketched in Fig. 4. The proposed solution requires a signal evaluation in two steps:

1. the gathering of reference signals to calculate the inverse filters and
2. the real measurement.

The first step needs to be performed only once for each receiver before any measurements are done. A reflector is placed in *k* chosen directions $\psi = \lfloor \psi_1, \psi_2, .., \psi_k \rfloor$ and in known distances to the receiver (*k* is chosen in accordance to the desired lateral resolution and the complexity of the system). For each direction the transfer function $H(\omega, \psi, r)$ and the inverse filter characteristics $I(\omega, \psi, r)$ are calculated from (3) and (4). The window function is selected as narrow as possible to limit the noise influence, but as wide enough to cover all possible frequency shifts. For the real measurement the targets are obtained from each receiver by threshold detection at each receiver. The target's location is calculated by triangulation from the delays between the echoes arrival times at the receivers. Additionally, a correction for the transmission loss is provided according to (2), resulting from the different distance $(r - r_r)$ of the real object and the reference reflector to the transducer. Each target echo is then filtered separately with the appropriate filter $I(\omega, \psi_i, r_r)$, ψ_i being the nearest of the preset directions to the estimated object direction (*i*=1..*k*) and the target velocity is determined by short time FFT.

EXPERIMENTAL RESULTS

In Fig. 5 an echo sequence is presented, which was obtained using 80 kHz ultrasound pulses in a room. Only one target was a moving object (slowly walking person), all others objects were fixed (room walls and equipment). For each of the detected 4 targets a FFT analysis has been performed. The frequency shifts and the corresponding velocities are given in Table I. The results for a measurement without correction algorithm show considerable

Table I:
Performance of the proposed inverse filter for a received echo signal

target	τ [ms]	r [m]	uncorrected f_d [Hz]	uncorrected v [m/s]	corrected f_d [Hz]	corrected v [m/s]
1	3.6	0.6	560	1.2	270	0.59
2	7.5	1.25	395	0.84	30	0.06
3	11.8	1.95	75	0.18	15	0.03
4	14.5	2.4	-300	-0.62	-60	-0.09

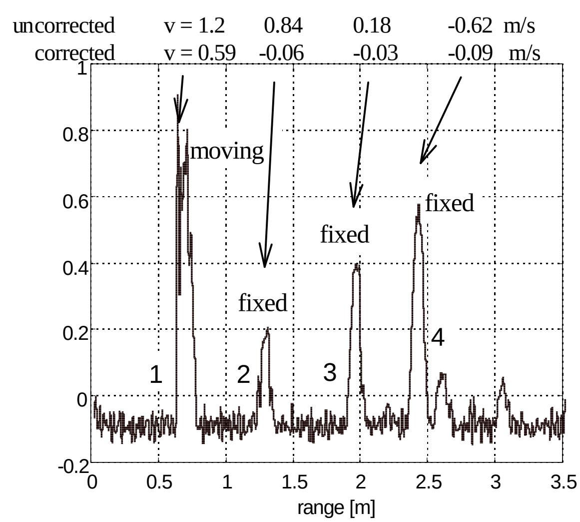

Fig.5: Echo envelope for 4 targets (1- moving, 2,3,4 -fixed) and their detected velocity before and after applying the correction algorithm

speed for all targets. The reason for this behaviour is the additional erroneous frequency shift. When the same situation is evaluated with the novel inverse filter technique, only target 3 appears to move. All other targets have velocities being nearly 0. (Due to the of the FFT analysis, the frequency results show a quantization Δf, which rises for higher samples rates and less FFT points. For a 8192 FFT and a 250kHz sample rate, Δf=15Hz. The resulting velocity uncertainty is Δv=0.03m/s, which, however, can be neglected for the regarded application.)

The novel technique was applied successfully to an intruder alarm system, detecting location and motion of objects in the observed room. Its performance guarantees a contrast between moving and fixed object sufficient to measure location and motion of persons correctly and to distinguish even small velocities from fixed object as furnishing or walls. Hence, the detection probability could be improved significantly.

In Table II results from a second example are given which show how the performance of the compensation algorithm depends on the chosen direction-sensitive inverse filter. A measurement situation with one transmitter/receiver pair having a 3-dB-width of the radiation pattern of about 30°. was evaluated. For one target in two different directions to the sensor the frequency shifts of the received echo in comparison with the transmitted signal frequency are enlisted. The results show, that the system's transfer function can be compensated successfully not only in case the filter corresponding to the right direction is applied, but with all inverse filters from within the radiation angle. This is because the transfer function of the overall system is corrupted mainly by the transducer's transient vibration modes and less for different angles of sound wave transmission. Hence, for most technical recognizing systems with relatively wide-angle transducers, to setup a few reference filter functions will be sufficient for a successful application of the compensation algorithm.

Table II:
Precision of frequency correction
depending on the reference filter direction ψ_r

Reference $I(\omega, \psi_r, r)$	Angle of target direction $\psi_m = 0°$		$\psi_m = 50°$	
ψ_r	uncorr. f_d [Hz]	corr. f_d [Hz]	uncorr. f_d [Hz]	corr. f_d [Hz]
0°	-90	0	540	350
10°	90	0	165	240
20°	120	15	105	-45
30°	105	0	105	30
40°	270	76	90	15
50°	355	385	30	15

CONCLUSIONS

A novel concept of a flexible inverse filter technique for a high precision pulsed wave ultrasonic range and velocity sensor has been developed. With the use of Wiener filters, adapted to specific direction of perception, precise location and velocity information of objects in a room are obtained. This simple technique gives significantly better results than conventional pulse-echo Doppler measurements and is essential especially for the detection of small velocities. Furthermore, the filter algorithm allows to use simple, short transmitting pulses and enables a flexible transducer configuration due to its robustness in a wide angle of observation.

REFERENCES

[1] S. Kuroda, A.Jitsumori, T.Inari, "Ultrasonic imaging system for robots using an electronic scanning method," *Robotica*, vol. 2, pp. 47-53, 1984

[2] W. Manthey, N. Kroemer, V. Mágori, "Ultrasonic transducers and transducer arrays for application in air," *Meas. Sci. Technol.*, vol. 3, pp. 249-261, 1992.

[3] R. Hickling, S.P. Marin, "The use of ultrasonics for gauging and proximity sensing in air," *Journal of the Acoustic Society of America*, Vol. 79(4), pp. 1151-1160, 1986.

[4] J.E. Wilhjelm, P.C. Petersen, "Target velocity estimation with FM and PW echo ranging Doppler systems (Part I- signal analysis, Part II- system analysis)," *IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 40, No. 4, pp. 366-372, 373-380, 1993

[5] G.S. Kino, *Acoustic waves: devices, imaging and analog signal processing*, Prentice-Hall, Englewood Cliffs, 1987

[6] Y. Murkami, B.T. Khuri-Yakub, G.S. Kino, J.M. Richardson, A.G. Evans, "The Application of Adaptive Filtering to Defect Characterization," *First Int. Symp. on Ultrasonic Materials Characterization*, Gaithersburg, MD, USA, pp. 23-28, 7-9 June 1978.

[7] V. Mágori, P.C. Eccardt, H. Ruser, M. Vossiek, "Direction-sensitive ultrasonic distance sensor using multimode stimulation of a single transducer," *Proc. IEEE Ultrasonic Symposium*, Seattle, USA, pp. 1045-1049, 1995