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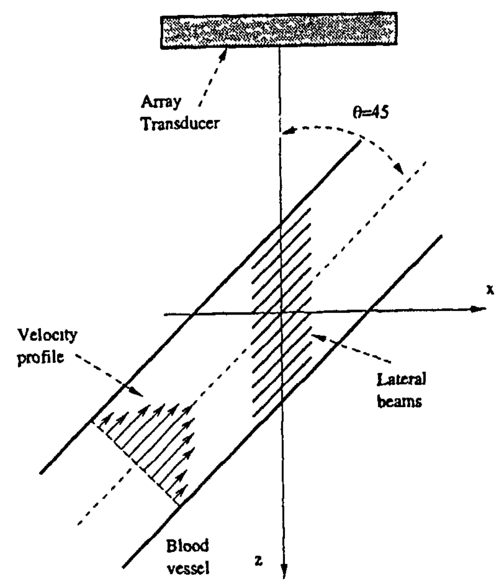
(54) Title: VECTOR VELOCITY ESTIMATION USING DIRECTIONAL BEAM FORMING AND CROSS-CORRELATION

(57) Abstract

The two-dimensional velocity vector using a pulsed ultrasound field can be determined with the invention. The method uses a focused ultrasound field along the velocity direction for probing the moving medium under investigation. Several pulses are emitted and the focused received fields along the velocity direction are cross-correlated. The time shift between received signals is found from the peak in the cross-correlation function and the velocity is thereby determined.



Focusing lines for obtaining the lateral beams in the case of a parabolic velocity profile

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Vector velocity estimation using directional beam forming and cross-correlation

Field of the invention

The invention relates to an apparatus and a method for determining the velocity vector of a remotely sensed object using either sound, in particular ultrasound, or electro-magnetic radiation. The movement of the object is determined by emitting and receiving a pulsed field focused in the direction of the velocity vector. By using a number of pulse emissions, the inter pulse movement can be estimated and the velocity found from the estimated movement and the time between pulses. The invention is based on the principle of using a directionally focused field for making the received signal influenced by motion along the direction of the movement.

Background of the invention

Medical ultrasound is extensively used for studying flow dynamics in the human body by using color flow mapping. The technique displays a color image of the flow superimposed on the normal anatomic B-mode image. Traditionally, the velocity component along the ultrasound beam direction is measured, and a flow transverse to the beam is not displayed, since it is not measured or estimated. An example of this is shown in Fig. 1, where the flows in the carotid artery and the jugular vein are displayed. The image is acquired with a convex array transducer, and the angles between flow direction and the ultrasound beam change over the image. Notice the change of estimated flow direction around the dashed line in both vessels due to the change of angle between the flow and the ultrasound beam. This is one of the main limitations of current ultrasound flow systems, since most vessels are parallel to the skin surface, and therefore it is a problem to get a sufficiently small angle between the flow and the beam. Also the flow is often not parallel to the vessel surface, and it is therefore difficult, if not impossible, to estimate the correct angle and compensate for it [1]. In European patent application EP 616 231 [2] the velocity is found through a cross-sectional area using a 2D matrix transducer that can focus on the individual areas in the cross-section. The volume flow through the cross-section is then found, but still only the velocity in direction of the ultrasound beam is estimated.

Several authors have attempted to remedy this artifact. Fox [3] suggested using two beams to find the transverse component. The system works well for large transducers and investigations close to the transducer, but the variance of the transverse component increases for situations with large depths and smaller transducers as used in cardiac scanning through the ribs. Trahey and co-workers [4] have suggested using speckle tracking in which a small search region in one image is correlated or compared to a subsequent image. This approach has problems in terms of frame rate, since images are compared, and the resolution of the velocity estimates can be low. Newhouse et al. [5] developed a method in which the total bandwidth of the received signal is affected by the transverse velocity. It is, however, often difficult to find this bandwidth due to the inherent noise in the signal.

Of special interest is the working by Bonnefous [6], which uses a number of parallel beams to find the transverse velocity. The approach does, however, not work for a velocity that is not orthogonal to the ultrasound beam direction.

In this invention a new technique using a focused signal in the direction of the velocity is used. The velocity is then found by acquiring two or more of these focused signals and cross correlating them to find the displacement between pulse emission, whereby the velocity can be determined.

Prior art approach

This section summarizes the article written in 1988 by Bonnefous [6], where a method for estimating the transverse velocity was suggested.

Transverse velocity estimation must perform a signal processing, where the effect of axial motion is negligible compared to the transverse one. The idea presented by Bonnefous requires a broad beam in emission (a plane ultrasound wave front), and a number of parallel identical beams, separated by a pitch w in the transverse direction, are generated in reception, see Fig. 2.

For a given depth z, the signal received $S_n(x,t)$ from the beam centered in $x = 0$ is

$$S_n(0,t) = \int p(x,t) D_n(x) dx \tag{1}$$

where $p(x,t)$ is the response of a scatterer located at x in the ultrasound beam centered at $x = 0$, and $D_n(x)$ is the scatterer distribution at the instant nT_{prf}, where T_{prf} is the pulse repetition period. In the same way, the signal received from the beam centered at $x = w$ is

$$S_n(w,t) = \int p(x-w,t) D_n(x) dx \tag{2}$$

If only a transverse uniform motion of the scatterers in considered, the displacement between two consecutive pulses nT_{prf} and $(n+1)T_{prf}$ will give the relation for the distribution of the scatterers

$$D_{n+1}(x) = D_n(x - v_x T_{prf}), \tag{3}$$

where v_x is the velocity of the scatterers. Combining equations (2) and (3) gives

$$\begin{aligned} S_{n+1}(0,t) &= \int p(x,t) D_{n+1}(x) dx \\ &= \int p(x,t) D_n(x - v_x T_{prf}) dx \\ &= \int p(x + v_x T_{prf}, t) D_n(x) dx \\ S_{n+1}(0,t) &= S_n(-v_x T_{prf}, t) \end{aligned} \tag{4}$$

For a beam centered in $x = w$ the relation between the consecutive signals is

$$S_{n+1}(w,t) = S_n(w - v_x T_{prf}, t) \tag{5}$$

The signal received in $x = w$ at the pulse time $(n+1)T_{prf}$ is, thus, the same as the signal received in a beam centered in $x = w - v_x T_{prf}$ at the pulse time nT_{prf}.

The correlation between the two signals $p(x,t)$ and $p(x-w,t)$ is an averaging of the received signals over the random scatterer distributions. The cross-correlation of the received signals from two adjacent signals is

$$C_1(w) = \sum_n \int_{t_0}^{t_0+\Delta t} S_n(0,t)S_{n+1}(w,t)dt$$
$$= \sum_n \int_{t_0}^{t_0+\Delta t} S_n(0,t)S_n(w - v_x T_{prf}, t)dt \qquad (6)$$
$$C_1(w) = C_0(w - v_x T_{prf}, t)$$

where $C_0(w) = \sum \int_{t_0}^{t_0+\Delta t} S_n(0,t)S_n(w,t)dt$, is the autocorrelation function averaged over a number of received lines, where the line number is denoted by n. The interval $(t_0, t_0+\Delta t)$ is the range gate selected for the received signals. Equation (6) show that the shift of C_1 compared with C_0 is the transverse displacement between the instants nT_{prf} and $(n+1)T_{prf}$. Therefore, the maximum of $C_1(w)$ is $C_1(v_x T_{prf}) = C_0(0)$.

For the general case, in which both axial and transverse motion takes place, the equation that relates the received signals from two successive pulses will be

$$S_{n+1}(w,t) = S_n(w - v_x T_{prf}, t - \frac{2v_z T_{prf}}{c}) \qquad (7)$$

Here $t_s = 2v_z T_{prf}/c$, is the time shift for the axial motion.

The cross-correlation and autocorrelation functions are generalized to two-dimensional functions and their expressions are

$$C_1(w,u) = \sum_n \int_{t_0}^{t_0+\Delta t} S_n(0,t)S_{n+1}(w,t+u)dt \qquad (8)$$

$$= \sum_n \int_{t_0}^{t_0+\Delta t} S_n(0,t)S_n(w - v_x T_{prf}, t - \frac{2v_z T_{prf}}{c} + u)dt \qquad (9)$$

$$C_0(w,u) = \sum_n \int_{t_0}^{t_0+\Delta t} S_n(0,t)S_n(w,t+u)dt \qquad (10)$$

The relation between the cross-correlation and the autocorrelation is

$$C_1(w,u) = C_0(w - v_x T_{prf}, u - \frac{2v_z T_{prf}}{c}) \qquad (11)$$

The two-dimensional determination of the velocity vector is performed by first finding the axial velocity and then the transverse component.

1. Axial velocity measurement: $C_1(0,u)$ is calculated and then, the time position of the correlation peak is determined as

$$\underset{u}{Max}\left[C_1(0,u)\right] = C_1(0,\frac{2v_z T_{prf}}{c}) \qquad (12)$$

2.Transverse velocity measurement: Fixing the value of the time coordinate to be $u = 2v_z T_{prf}/c$ in $C_1(w,2v_x T_{prf}/c)$, the peak for the transverse correlation is determined as

$$\underset{w}{Max}\left[C_1(w,\frac{2v_z T_{prf}}{c}\right] = C_1(v_x T_{prf},\frac{2v_z T_{prf}}{c}) \qquad (13)$$

This process can be generalized to measure the three-dimension velocity vector. New parallel beams along the y-axis should be used, and the cross-correlation function will be a three-dimensional function of the type $C_1(w,h,u)$. The problem with this approach is, however, that a spatially invariant velocity field is assumed, which is not the case in the human body.

Summary of the invention

This section describes the approach of the invention for finding the transverse component of the blood velocity. The invention presupposes that the direction of movement is known. In medical ultrasound a two-dimensional image including a blood vessel of interest is produced. The operator will then manually indicate the position and direction of the blood vessel to the system, or this information can be obtained automatically.

In a first embodiment of the invention, wave energy is emitted in a predetermined direction towards a moving object or a collection of moving objects, which will interact with the wave energy, whereby the wave energy will be scattered or reflected. Moving objects thus interacting with emitted wave energy are often referred to as "scatterers". Scattered or reflected wave energy will be received and processed to yield the desired estimate or measurement of velocity of the moving object or a collection of moving objects. The velocity of any scattering or reflecting object, whether emitting it self or not, can be measured.

The main idea of the first embodiment of the invention is the creation of a plurality of focal points, which together form a focused line or beam in the direction of the velocity vector that will track the motion of the scatterers. The generation of this focused beam requires a broad beam in emission and multiple foci along the line in reception. This can be achieved with a multi-element transducer. The focusing line is situated over the region of interest, where the motion of the scatterers occurs, see Fig 3. The method of the invention presupposes that scatterers, whose motion is tracked, have the same velocity along the whole length of the line. When measuring a laminar parabolic flow or other spatially variant velocity fields, the focus line therefore has to be oriented in the direction of the flow lines.

The lateral beam is calculated during reception by delaying and adding responses from the individual elements of the array. The delays are found for each focus point by calculating the time it takes for the ultrasound wave to travel from each transducer elements to the focus point and back to the transducer. Lateral beams are in this way constructed for each of the emitted pulses.

The velocity is estimated from the cross-correlation of two consecutive lateral signals. Hereby the displacement of the signals corresponds to an estimate of the distance traveled by the scatterers in the lateral beam direction. Since the lateral beams are situated along the flow stream-lines, the complete velocity magnitude can be directly estimated.

In a second embodiment the velocity of a moving object or a collection of moving objects emitting wave energy while moving, is measured. No emission of wave energy is required, but rather the wave energy emitted by the moving object is received and processed to yield the desired estimate or measurement of velocity of the moving object or a collection of moving objects. The main idea of the second embodiment of the invention is the creation of a plurality of focal points, which together form a focused line or beam in the direction of the velocity vector that will track the motion of the emitting object or objects.

Measurement principle of the invention

This section derives a mathematical model of the tilted beam approach. The measurement situation is depicted in Fig. 4. The figure shows a multi-element transducer with N elements. The vector from the origin of reference to the physical center of element i is $\vec{P}_i$. The vector indicating the position of the focus points in the line is $\vec{P}_j$ and is given by

$$\vec{P}_i = (x_i, y_i, z_i), \qquad i = 1 \ldots N$$
$$\vec{P}_j = (x_j, y_j, x_j), \qquad j = 1 \ldots M$$
$$\vec{P}_{ij} = \vec{P}_j - \vec{P}_i = (x_j - x_i, y_j - y_i, z_j - z_i), \tag{14}$$

where $\vec{P}_{ij}$ is the vector from element i to the focus point j, and M is the number of focus points along the line. The time it takes for the ultrasound pulse to get from the element i to the focus point j and back to the element i is

$$t_{ij} = \frac{2}{c}\left|\vec{P}_{ij}\right| = \frac{2}{c}\sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2} \tag{15}$$

The received backscattered signal in element i that corresponds to the ultrasound pulse emitted in nT_{prf}, can be written as $r_n(\vec{P}_i, t)$, where t indicates the time since pulse emission.

Assuming linearity the value of the field in a focus point j, is calculated by adding the responses found in each element i for the appropriated delay time t_{ij}

$$s_n(\vec{P}_j) = \sum_{i=1}^{N} r_n(\vec{P}_i, t_{ij}) \tag{16}$$

For the next ultrasound pulse $(n+1)T_{prf}$, the value of the field in the same point will be

$$\begin{aligned} s_{n+1}(\vec{r}_j) &= \sum_{i=1}^{N} r_{n+1}(\vec{r}_i, t_{ij}) \\ &= \sum_{i=1}^{N} r_n(\vec{r}_i, t_{ij} - 2\frac{v_{i,axis}}{T_{prf}}), \end{aligned} \tag{17}$$

where $v_{i,axis}$ represents the component of the velocity of a scatterer placed in $\vec{r}_j$, projected on the $\vec{r}_{ij}$ direction. The expression above uses the relation between two consecutive backscattered signals. The relation $t_{ij} - 2v_{i,axis}/T_{prf}$ will correspond to a delay value t_{ik}, where k is another point on the focusing line. If $\vec{d}_l$ is a unitary vector in the direction of the lateral beam, and l_s is the distance between the points j and k, then $\vec{r}_j = \vec{r}_k + l_s\vec{d}_l$ and the following relation is found

$$\begin{aligned} s_{n+1}(\vec{r}_j) &= \sum_{i=1}^{N} r_n(\vec{r}_i, t_{ij} - 2\frac{v_{i,axis}}{T_{prf}}) \\ &= \sum_{i=1}^{N} r_n(\vec{r}_i, t_{ik}) \\ s_{n+1}(\vec{r}_j) &= s_n(\vec{r}_k) = s_n(\vec{r}_j - l_s\vec{d}_l) \end{aligned} \tag{18}$$

The beam processing is performed on digital signals and the sampled version of the beam formed signal is denoted $R_n[l]$. The signal calculated for the pulse at time $(n+1)T_{prf}$ is a shifted version of the lateral signal for the pulse at time nT_{prf}. The shift in position can be calculated from the cross-correlation of two consecutive signals $S_1[l]$ and $S_2[l]$:

$$\begin{aligned} R_{12} &= \frac{1}{M}\sum_{l=0}^{M-1} S_1[l]S_2[l+n] \\ &= \frac{1}{M}\sum_{l=0}^{M-1} S_1[l]S_1[l+n-l_s] \\ &= R_{11}(k-l_s) \end{aligned} \tag{19}$$

The shift in position is then determined by the index of the peak of the cross-correlation function

$$\underset{k}{Max}\left[R_{12}(k)\right] = \underset{k}{Max}\left[R_{11}(k - l_s)\right] \Rightarrow k = \hat{l}_s \quad (20)$$

The cross-correlation can be improved by averaging over several estimates of R_{12}, since the velocity of the scatterers can be considered constant for several pulses. The estimated mean velocity between two consecutive pulses is:

$$\hat{v} = \frac{\hat{l}_s dl}{T_{prf}} \quad (21)$$

where dl is the sampling interval along the lateral beam direction.

Functionality of the invention

The invention was simulated using the simulating program Field II [7]. The lateral beam is directly calculated with a focusing strategy that can be achieved with a regular array transducer. The method was first tested for a blunt profile of the scatterers and then for a parabolic profile.

Estimation of the velocity for a blunt profile

In the beginning, the lateral beam was intended as an attempt to estimate the transverse velocity component $(\hat{v}_x)$. Since $\hat{v}_z$ could be obtained from the time-shift estimation method, the velocity in the x-z plane will be estimated as $\vec{v}_{est} = (\hat{v}_x, \hat{v}_z)$.

The estimation of v_x can be obtained in the case of a blunt profile using a focusing line perpendicular to the z-axis. Two lateral signals are generated for each ultrasound pulse. The second one has been compensated for the axial movement that took place in the pulse interval time. The cross-correlation of the first signal obtained from pulse i with the compensated signal from pulse i+1 reveals the transverse motion of the scatterers between the two pulses.

The calculation of the lateral beam and the estimation of the velocity are explained below. The last part shows the results obtained for different vessel inclinations and for two different series of parameters.

Simulations for a blunt profile

The simulation is performed in the following way:

1. The transducer used for the simulation is a linear array transducer with 64 elements of dimensions: 0.25 mm width, 5 mm height and a kerf or separation between elements of 0.05 mm. It gives the possibility of electronic focusing and apodization. A Hanning apodization is used for both emission and reception. The emit focus is set to be at an infinite distance from the transducer, so that a plane wave front is found at the measurement area. Short ultrasound pulses are simulated to be emitted every T_{prf} seconds.

2. The generation of simulated data must include an artificial phantom consisting of point scatterers. This phantom simulates a blood vessel close to the skin surface at a depth of 30 mm. The angle between the blood vessel and the axial ultrasound beam is called θ, see Fig. 4. The phantom will be propagated a distance $\Delta r = vT_{prf}$ in the interval between two consecutive ultrasound pulse emissions to simulate the displacement of the scatterers. In the first simulations a blunt profile is considered, so that all scatterers move at the same velocity that was set to be 0.5 m/s.

3. For every ultrasound pulse, an individual simulation for each element of the transducer is done by the Field II program and stored. The field program is called 64 times for each of the transducer elements and for each pulse emission.

4. The focused beam is calculated as a transverse beam situated at a depth of 30 mm, in the middle of the region of interest. It uses the data obtained in the previous step. The line, transverse to the ultrasound beam has the same length as the transducer, i.e. 20 mm. The separation between two focus points was chosen to be $dx = 0.02$ mm, which gives a total of 1000 samples for the transverse beam. The value of the field in each focus point is found by calculating the time that it takes the ultrasound wave to travel from each of the transducer elements to the field point and back to the transducer. This is

$$delay = \frac{2}{c}\sqrt{(x_f - x_c)^2 + (y_f - y_c)^2 + (z_f - z_c)^2} \qquad (22)$$

where (x_c, y_c, z_c) are the positions of the center of the physical elements of the aperture and (x_f, y_f, z_f) the position of each point in the transverse line. Three delay lines for the first, middle and last points of the transverse line have been plotted in Fig. 5 (continuous line).

The field value in each focus or transverse sampling point is the sum of the fields values obtained for each channel at the times that corresponds to the calculated delay line. The signal constructed this way is stored for each ultrasound emission.

At the same time and for each emission, a second signal is synthesized. It corresponds to the lateral beam where the axial movement of the scatterers has been compensated for. In this case the delays are

$$delay' = \frac{2}{c}\sqrt{(x_f - x_c)^2 + (y_f - y_c)^2 + (z_f - z_c)^2} - \frac{2v_z}{c}T_{prf} \tag{23}$$

These new delay lines are plotted as dashed lines in Fig. 5. The axial velocity (v_z) needs to be estimated before the calculation of the compensated delay lines.

Estimation of the velocity

The signals obtained from the simulation are used to estimate the velocity. The velocities are estimated by cross-correlating two consecutive signals in which the second signal is compensated for the axial motion that takes place during the pulse time interval. The position of the cross-correlation peak then indicates the shift of the signals.

The transverse velocity is found from

$$\hat{v}_x = \frac{dl}{T_{prf}} \cdot n_{\text{int}}, \tag{24}$$

where n_{int} is the interpolated index found by fitting a parabola around the maximum in the cross-correlation function [8].

Simulations and results

Figure 9 shows the result of the simulations. They were performed for a blunt profile and for a scatterer velocity equal to $v = 0.5$ m/s. The scatterer patterns were generated for seven different angles between the vessel and the axial beam. The received signals were found for 20 different pulse emissions. The cross-correlation estimator used 4 consecutive lines. This gave a total of 16 estimates for each velocity value. The dashed arrows point to $(mean(\hat{v}_x), mean(\hat{v}_z))$ for each angle, while the continuous line arrows represent the true values. The standard deviation is represented for each estimated point as the axis of the following ellipse:

$$\left(\frac{mean(\hat{v}_x)}{std(\hat{v}_x)}\right)^2 + \left(\frac{mean(\hat{v}_z)}{std(\hat{v}_z)}\right)^2 = 1 \qquad (25)$$

The simulation parameters are shown in Table 1 and the results are plotted in Fig. 9 and listed in Table 2.

Estimation of the velocity for a parabolic profile

The received signals are now focused along the flow direction. The lateral beams are tilted in order to follow the motion of the scatterers, see Fig. 3. The inclination of the vessel has to be known or estimated with a B-mode image for the calculation of the flow beams.

In the simulation a box of 20 x 10 x 20 mm^3 is created. It contains 10 point-scatterers per cubic wavelength. The position and amplitude of the scatterers are randomly generated. The box of scatterers is rotated an angle $\varphi = \pi/2 - \theta$ to simulate the vessel inclination. The 'vessel' has a radius of 5 mm and is situated at a depth of 30 mm from the transducer. The scatterers that lie within the vessel wall are propagated between two consecutive pulses. The velocity profile is parabolic and the velocity in the center of the vessel is 0.5 m/s.

For each ultrasound pulse i, the data, with the positions and amplitudes of the scatterers, is loaded. Then, a scan for each of the channels of the array transducer is done. Finally, the delay lines for each focusing line are calculated and the flow beams are generated by adding the responses that correspond to the delay lines.

The transducer used was a linear array with 64 elements as described in Section 5.1. The parameters used for the simulation are listed in Table 3.

The focused lines had a length of 10 mm. They are rotated to have the same direction as the flow lines (see Fig 7). They have to cover an axial distance of at least

$$Z(\Theta) = \frac{2R}{\sin\Theta} \tag{26}$$

This length assures that there will be flow-beams in all the cross-section of the vessel. For small values of θ, the axial range-gate has to be increased. $Z(\theta)$ is divided in small segments, and for each of them a focusing line is calculated. The axial and lateral interval values used in the simulation are given in Table 4.

The velocity estimates are found from the simulated data. The velocity map is calculated by the cross-correlation of two received signals. These signals have been plotted in Fig. 8 for five different depths. The continuous lines represents the first signals and the dashed lines the second. The motion of the scatterers can be appreciated by the displacement of the signals. In the center of the vessel ($r = 0$) the largest shift in position is observed. This shift decreases with the distance to the axis, and a parabolic profile can be recognized.

Once the cross-correlation function is calculated and averaged over a number of lines (4, 10, 20 or 100 for this simulation), the index of the maximum in the cross-correlation is obtained and interpolated, and the velocity is found from (24).

The minimum velocity that can be obtained is limited by the lateral sampling interval (dl), and the maximum value is determined by the lag in the cross-correlation function:

$$v_{\min} = \frac{dl}{T_{prf}} \tag{27}$$

$$v_{\max} = \frac{dl}{T_{prf}} \cdot lag \tag{28}$$

For the values introduced in the simulation: $dl = 0.01$ mm, $T_{prf} = 1/3500$ s and a sampling transverse line of 10 mm, this gives 10/0.01=1000 sampling points and the limits for the velocity estimation are

$$v_{min} = 0.035 \text{ m/s} \tag{29}$$

$$v_{\max} = 0.035 \cdot 1000 = 35 \text{ m/s} \tag{30}$$

The simulation was repeated for four inclinations of the vessel, θ=30, 45, 60, and 90°. For each angle, the estimates were found when averaging over 4, 10, 20 or 100 lines in the cross-correlation, which gave a total of 96, 90, 80 or 1 velocity estimates respectively for every lateral beam. The results are plotted in figures: 10, 11, 12, and 13. The thick line is the true velocity profile, the continuous line is the mean of the estimates, and the dotted lines are the standard deviations of the estimates.

The error in the velocity estimation is represented by the mean and the standard deviation of the vertical distance between the true and the estimated velocity profile (Table 5). The values in the table are when using 4 lines for calculating the cross-correlation.

Tables

Center frequency f_0[Hz]	Wavelength $\lambda = c/f_0$ [m]	Number of cycles M	Sampling frequency f_s [Hz]	Pulse repetition period T_{prf} [s]	Number of scatterers N	Transversal interval dx [m]
$3 \cdot 10^6$	$0.51 \cdot 10^{-3}$	2	$100 \cdot 10^6$	1/3500	5000	$0.01 \cdot 10^{-3}$

Table 1: Parameters used for the blunt profile simulation. The emit focal distance is 150 mm.

θ [deg]	0	30	60	90	135	-135	-45
True v_x [m/s]	0	0.25	0.43	0.5	0.35	-0.35	-0.35
Mean $[\hat{v}]_x$ [m/s]	0.067	0.245	0.407	0.449	0.342	-0.303	-0.309
Std $[\hat{v}]_x$ [m/s]	0.008	0.033	0.014	0.019	0.018	0.023	0.016
Error [%]	-	-2	-5.3	-10.2	2.2	13.4	11.7
Accuracy [%]	11.9	13.4	3.4	4.2	5.2	7.5	5.1

Table 2: Values of the real transverse velocity and the estimates mean and standard deviation for 5000 scatterers and an emit focal distance of 150 mm. The error is calculated as: $(mean(\hat{v}_x) - v_x)/v_x$, and the accuracy is $mean(\hat{v}_x - v_x)/std(\hat{v}_x)$.

Center frequency f_0 [Hz]	Wavelength $\lambda = c/f_0$ [m]	Number of cycles M	Sampling frequency f_s [Hz]	Pulse repetition period T_{prf} [s]	Focal distance F [m]
$3 \cdot 10^6$	$0.51 \cdot 10^{-3}$	2	$100 \cdot 10^6$	1/3500	150

Table 3: Parameters used for the parabolic profile simulation.

Lateral line length [m]	Lateral interval [m]	Axial length [m]	Axial interval [m]
$10 \cdot 10^{-3}$	$0.01 \cdot 10^{-3}$	$Z(\theta)$	$0.1 \cdot 10^{-3}$

Table 4: Values of the lateral and axial intervals used in the simulations.

θ [deg]	30	45	60	90
Mean $\lvert\hat{v} - v\rvert$ [m/s]	0.081	0.056	0.04	0.073
Std $\lvert\hat{v} - v\rvert$ [m/s]	0.047	0.038	0.029	0.029

Table 5: Mean and standard deviation of the distance between the true profile and the estimated one. They are calculated for a different cross-section distance for each of the angles so that only the significant part of the plots are taken into account : r ∈ [−8.5,6] for θ=30°, r ∈ [−8.3,8.3] for θ=45°, r ∈ [−8,8] for θ=60°, r ∈ [−5,5] for θ=90° (r indicates distance to the center of the vessel in [mm]).

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Claims

1. An apparatus for measuring the velocity of a moving object or a collection of moving objects moving in a predetermined direction and at a predetermined distance, the apparatus comprising:

a generator for generating excitation signals,

an emitting transducer for transforming said excitation signals into wave energy and for emitting said wave energy in a predetermined direction of propagation,

a receiving transducer for receiving, from said moving object or objects, signals generated by interaction with said wave energy emitted from said emitting transducer,

wherein said emitting transducer and said receiving transducer have respective sensitivities which in combination give a focused sensitivity focused in a region comprising the predetermined direction at the predetermined distance.

2. An apparatus according to claim 1 wherein said wave energy is pulsed wave energy.

3. An apparatus according to claim 1 wherein said wave energy is sound energy.

4. An apparatus according to claim 1 wherein said sound energy is ultrasound energy.

5. An apparatus according to claim 1 wherein said wave energy is electromagnetic energy.

6. An apparatus according to claim 1 wherein said emitting transducer is an array transducer including a plurality of emitting transducer elements.

7. An apparatus according to claim 6 further comprising an emit beam former for receiving said generating excitation signals and for supplying each of said plurality of emitting transducer elements with individual excitation signals each having a predetermined time delay relative to the others of said individual excitation signals.

8. An apparatus according to claim 1 wherein said receiving transducer is an array transducer including a plurality of receiving transducer elements.

9. An apparatus according to claim 8 further comprising a receive beam former for receiving signals from said plurality of receiving transducer elements and for delaying each of said signals from said plurality of receiving transducer elements individually relative to the others of said signals from said plurality of receiving transducer elements.

10. An apparatus according to claim 7 wherein said individual excitation signals have time delays resulting in focused wave energy being emitted.

11. An apparatus for measuring the velocity of a moving object or a collection of moving objects emitting wave energy while moving in a predetermined direction and at a predetermined distance, the apparatus comprising:

a receiving transducer for receiving signals emitted by said moving object or objects,

wherein said receiving transducer has a focused receiving sensitivity focused in a region comprising the predetermined direction at the predetermined distance.

12. An apparatus according to claim 11 wherein said signals are sound signals.

13. An apparatus according to claim 11 wherein said sound signals are ultrasound signals.

14. An apparatus according to claim 11 wherein said signals are electromagnetic signals.

15. An apparatus according to claim 11 wherein said receiving transducer is an array transducer including a plurality of receiving transducer elements.

16. An apparatus according to claim 15 further comprising a receive beam former for receiving signals from said plurality of receiving transducer elements and for delaying each of said signals from said plurality of receiving transducer elements

individually relative to the others of said signals from said plurality of receiving transducer elements.

17. A method for measuring the velocity of a moving object or a collection of moving objects moving in a predetermined direction and at a predetermined distance, the method comprising:

emitting excitation signals of pulses of wave energy in a predetermined direction of propagation, whereby at least part of the wave energy will interact with the moving object or objects,

receiving, from said moving object or objects, reflected signals resulting from interaction of emitted wave energy with the moving object or objects,

wherein the emission of excitation signals and the reception of reflected signals have respective sensitivities which in combination give a focused sensitivity focused in a region comprising the predetermined direction at the predetermined distance.

18. A method according to claim 17 wherein said wave energy is pulsed wave energy.

19. A method according to claim 17 wherein said wave energy is sound energy.

20. A method according to claim 17 wherein said sound energy is ultrasound energy.

21. A method according to claim 17 wherein said wave energy is electromagnetic energy.

22. A method according to claim 17 wherein said emitting transducer is an array transducer including a plurality of emitting transducer elements.

23. A method according to claim 22 further comprising an emit beam former for receiving said generating excitation signals and for supplying each of said plurality of emitting transducer elements with individual excitation signals each having a predetermined time delay relative to the others of said individual excitation signals.

24. A method according to claim 17 wherein said receiving transducer is an array transducer including a plurality of receiving transducer elements.

25. A method according to claim 24 further comprising a receive beam former for receiving signals from said plurality of receiving transducer elements and for delaying each of said signals from said plurality of receiving transducer elements individually relative to the others of said signals from said plurality of receiving transducer elements.

26. A method according to claim 23 wherein said individual excitation signals have time delays resulting in focused wave energy being emitted.

27. A method for measuring the velocity of a moving object or a collection of moving objects emitting wave energy while moving in a predetermined direction and at a predetermined distance, the method comprising:

receiving signals emitted from said moving object or objects

wherein the reception of reflected signals have a focused sensitivity focused in a region comprising the predetermined direction at the predetermined distance.

28. A method according to claim 27 wherein said wave energy is sound signals.

29. A method according to claim 28 wherein said sound signals are ultrasound signals.

30. A method according to claim 27 wherein said wave energy is electromagnetic signals.

31. A method according to claim 27 wherein signals emitted from said moving object or objects are received by an array transducer including a plurality of receiving transducer elements.

32. A method according to claim 31 further comprising a receive beam forming of received signals from said plurality of receiving transducer elements and delaying each of said signals from said plurality of receiving transducer elements individually

relative to the others of said signals from said plurality of receiving transducer elements.

Figures

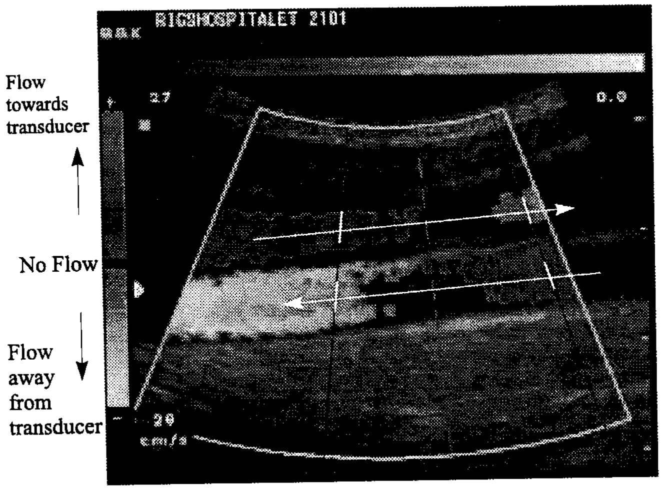

Figure 1: Color flow image of the carotid artery and the jugular vein scanned with a convex array transducer. Notice the change of the angle between the ultrasound beam and the velocity vector around the dashed line.

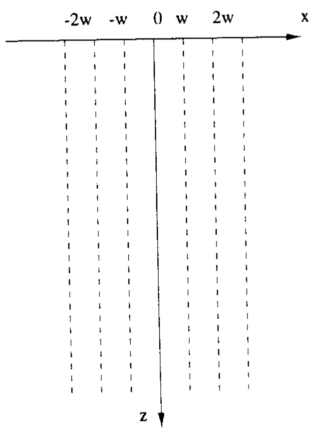

Figure 2: Parallel beams in reception

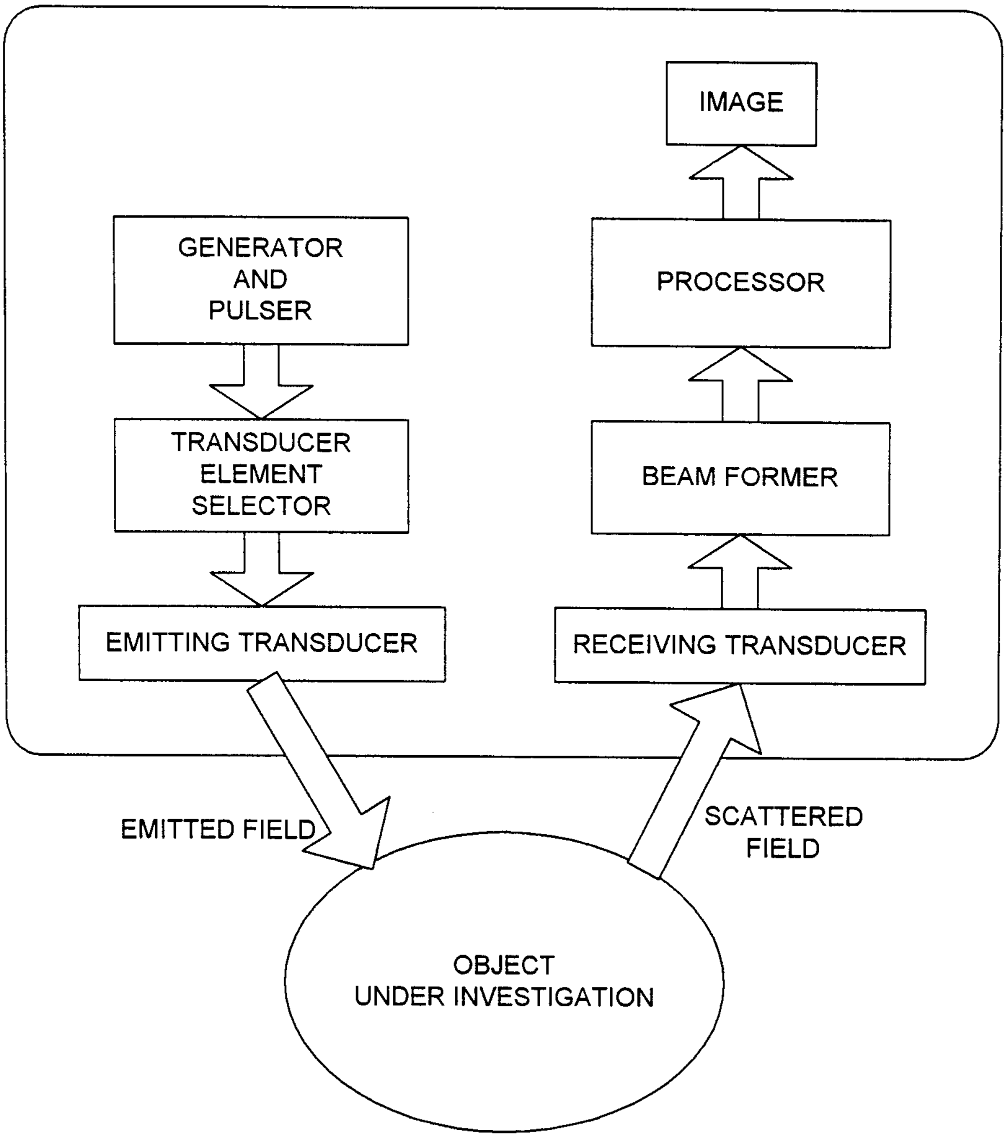

Fig. 1A: Schematic block diagram of the apparatus of the invention

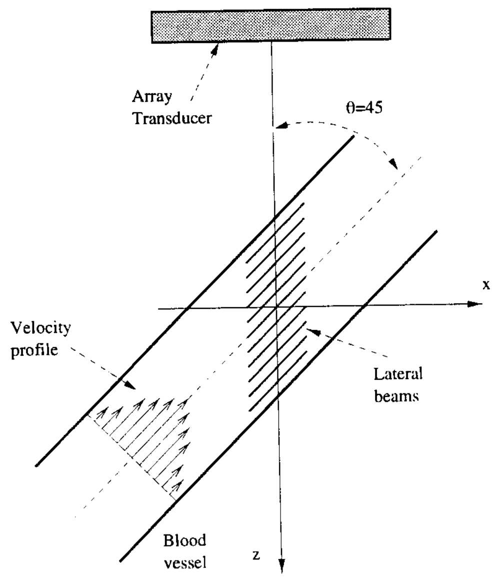

Figure 3: Focusing lines for obtaining the lateral beams in the case of a parabolic velocity profile

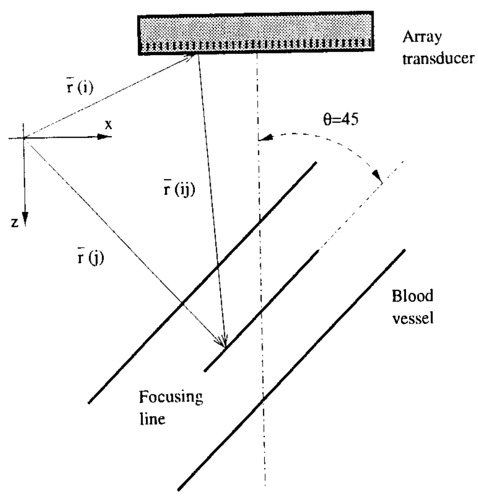

Figure 4: Coordinate system for the lateral beam measurement principle

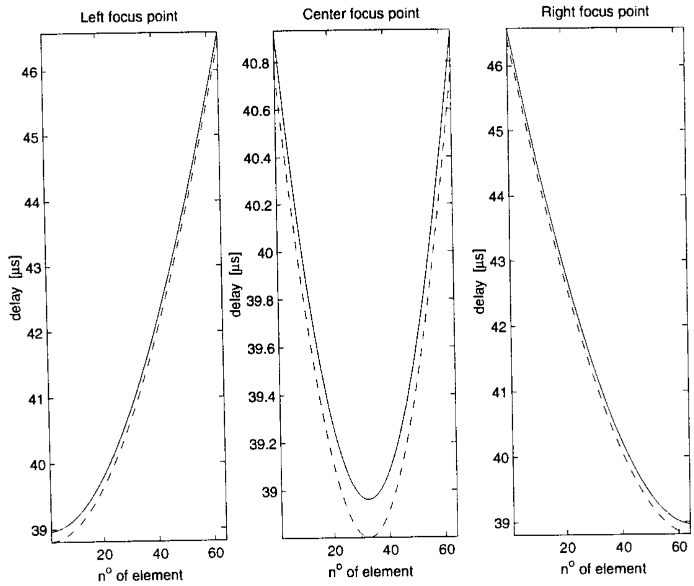

Figure 5: Delay lines for the first, middle and last focus point of a transverse line of length 10 mm, perpendicular to the z-axis (continuous line). The dashed lines represent the delay lines compensated for the axial velocity of the scatterers when $\theta=30^o$, $v = 0.5$ m/s and $T_{prf}=1/3500$ s.

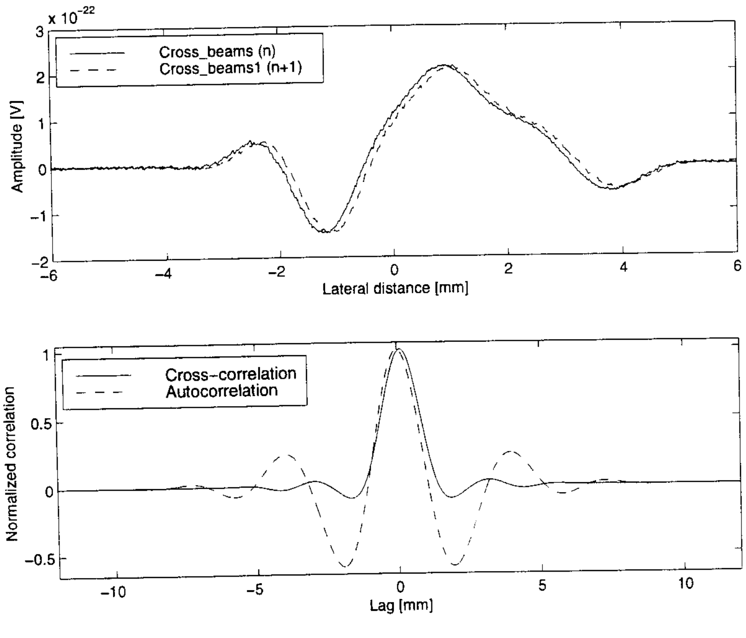

Figure 6: The top graph shows two consecutive lateral signals, where the second signal is compensated for the axial movement. The displacement, thus, corresponds to the transverse motion. It has been evaluated in the bottom graph by the cross-correlation method. Simulation was performed for $\theta=60^o$, $v=0.5$ m/s and $dx=0.01$ mm.

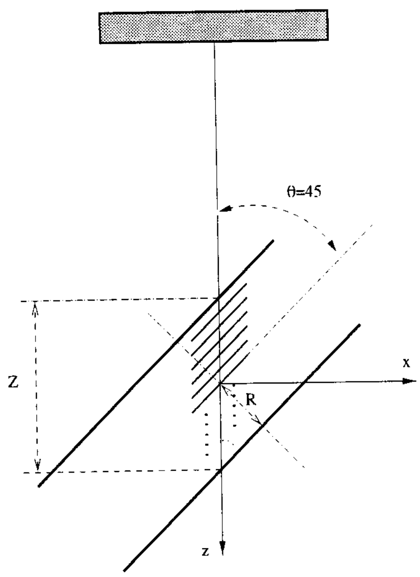

Figure 7: Definition of depth in the vessel.

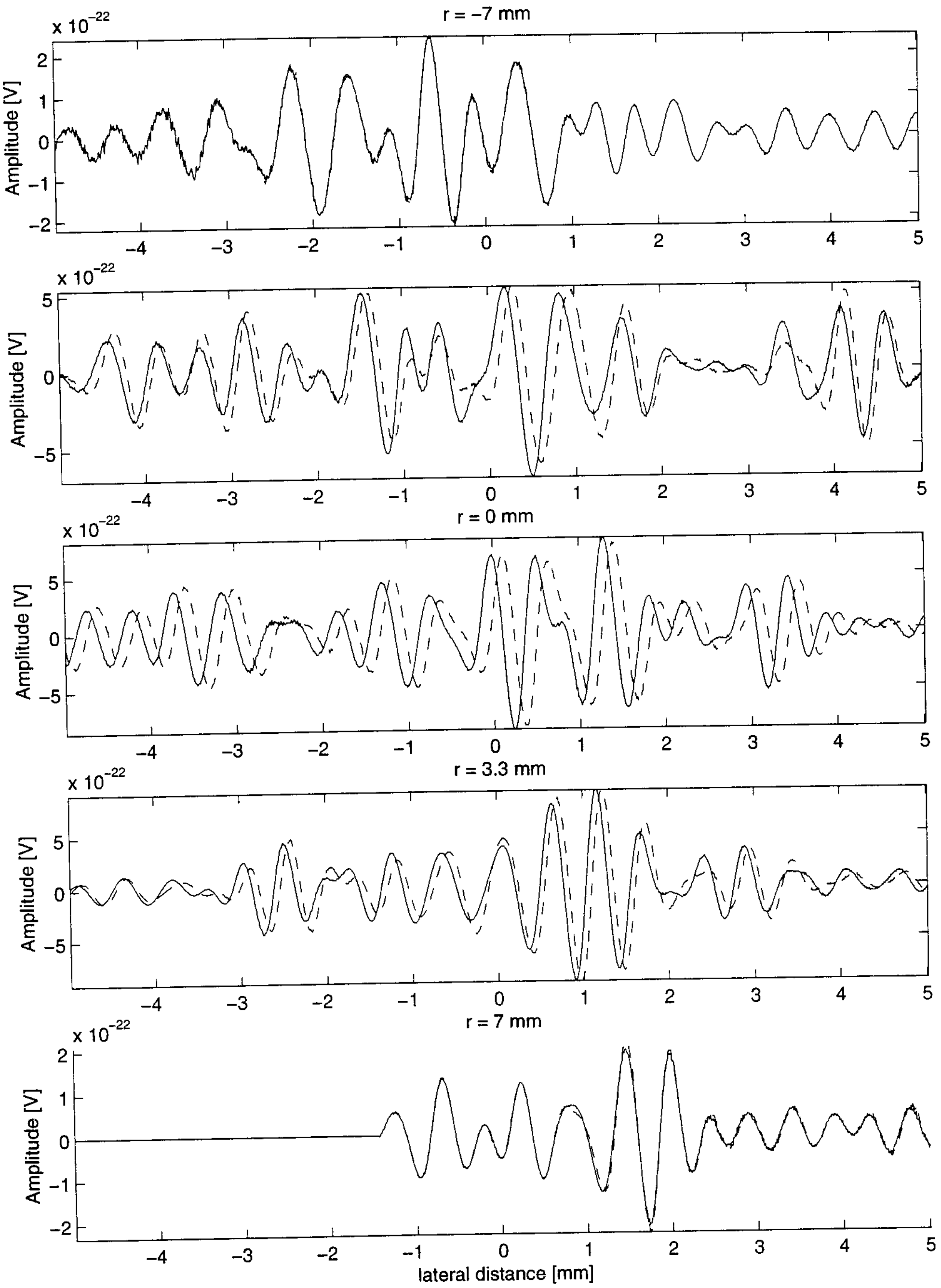

Figure 8: Evolution of the lateral signals from two ultrasound pulses: pulse (i) is the continuous line and pulse ($i+1$) is the dashed line. Five different points of the cross-section of the vessel are shown. The distance is measured from the center axis of the vessel. The data corresponds to an inclination of the vessel of $\theta = 60^o$, see also Fig. 12.

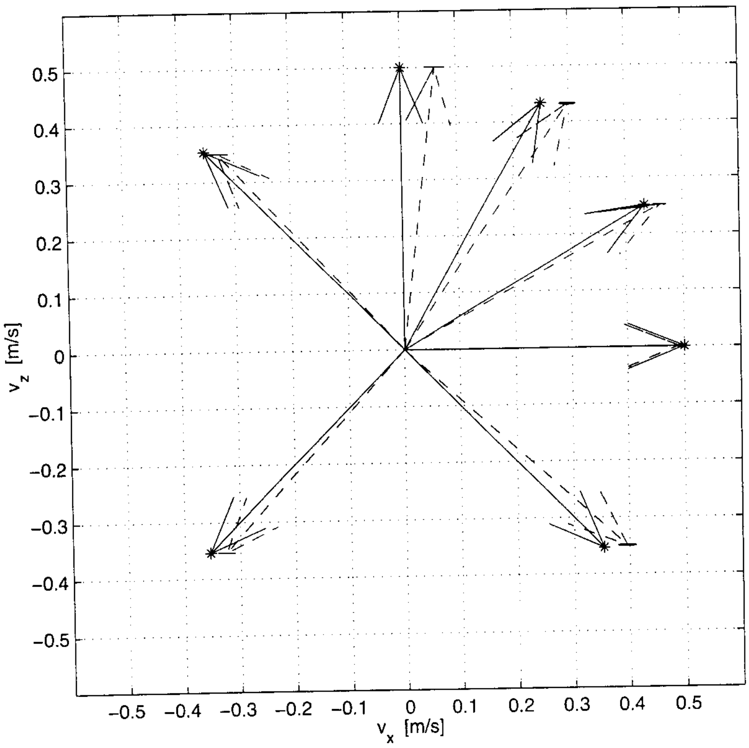

Figure 9: The continuous line arrows show the real velocity and the dashed line arrows show the estimated velocity: $\vec{v}_{est} = (\hat{v}_x, \hat{v}_z)$ for plug flow. The angle θ is measured clockwise from the vertical axis.

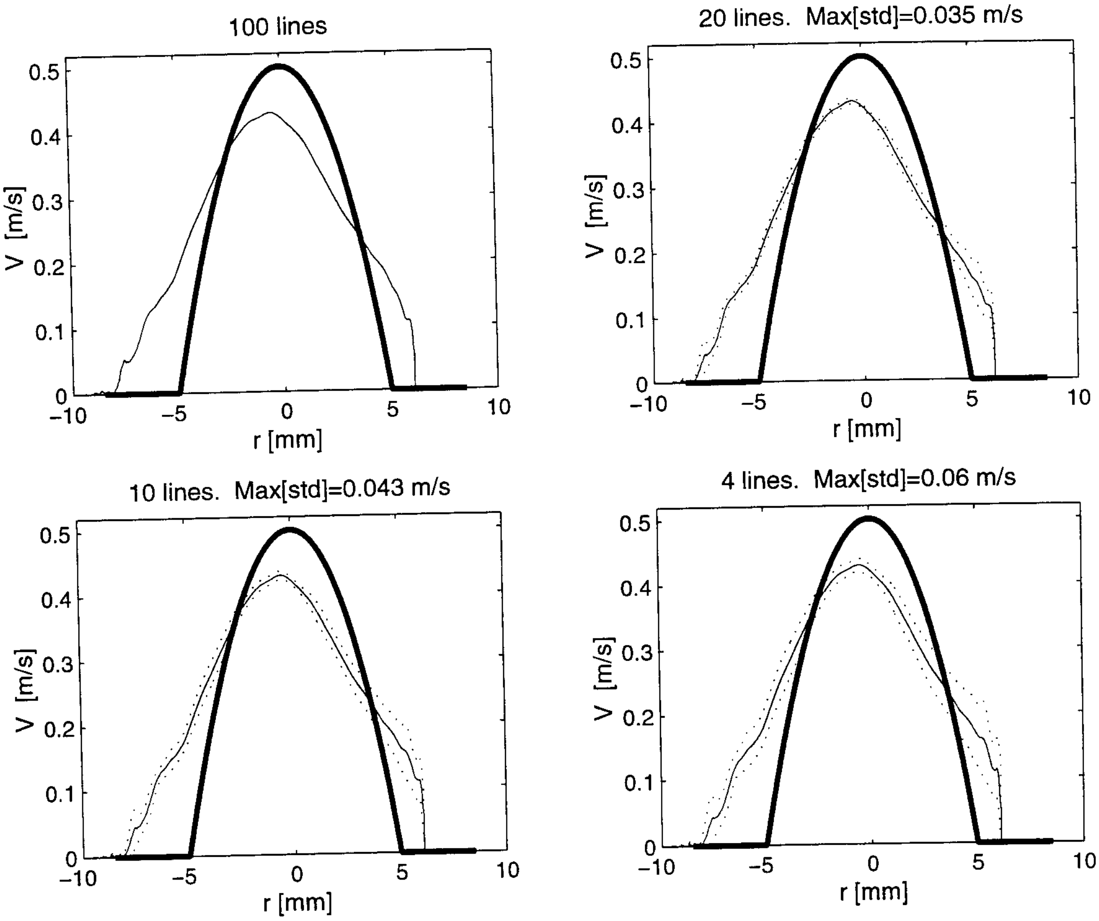

Figure 10: Estimated velocity profiles for θ=30° using 100, 20, 10 and 4 lines. The thick line indicates the true velocity profile, the continuous line is the mean of the estimates, and the dotted lines are the standard deviations.

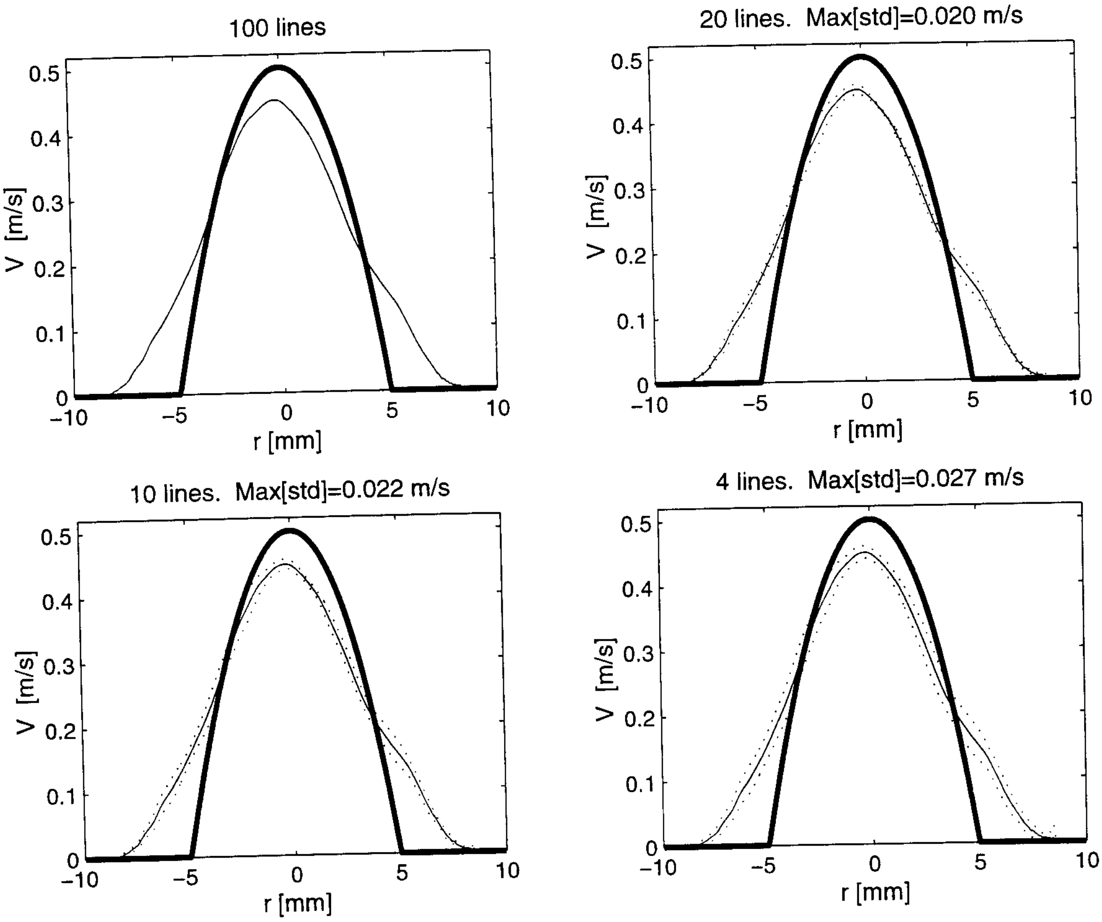

Figure 11: Estimated velocity profiles for θ=45° using 100, 20, 10 and 4 lines. The thick line indicates the true velocity profile, the continuous line is the mean of the estimates, and the dotted lines are the standard deviations.

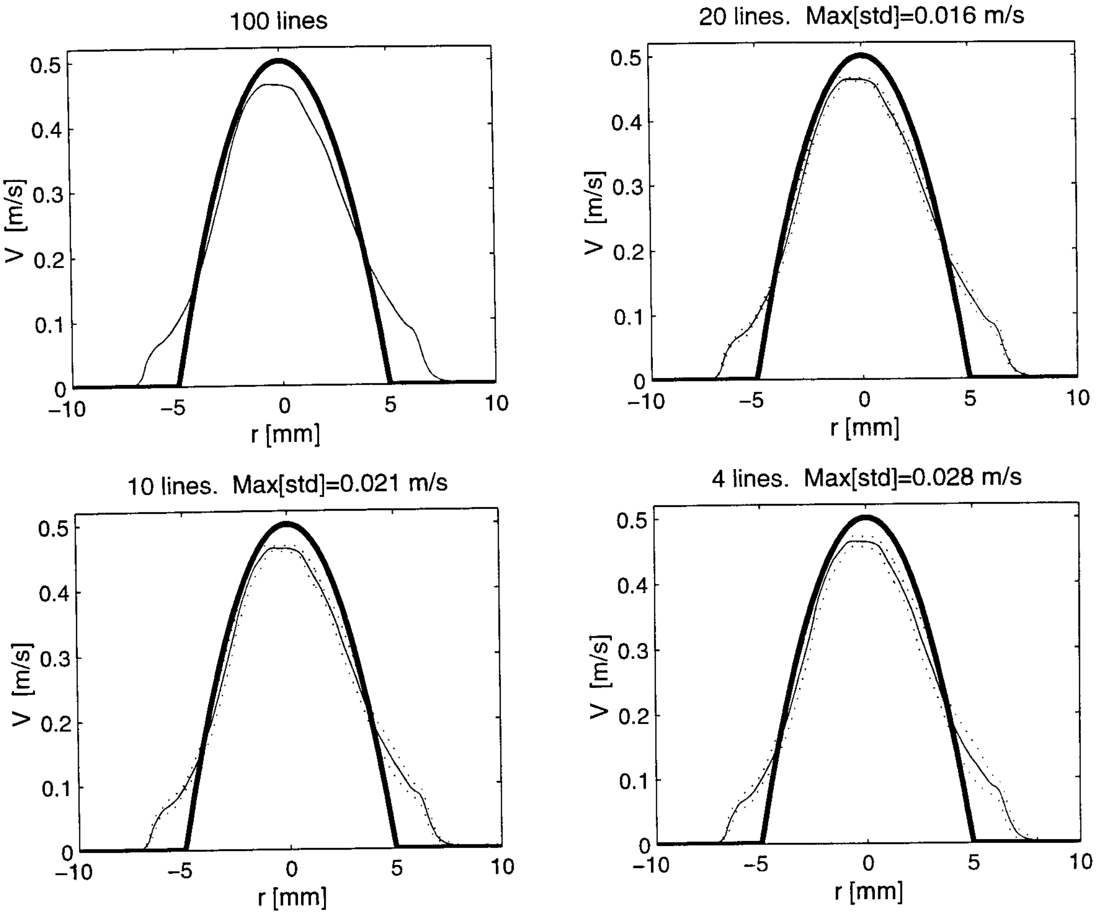

Figure 12: Estimated velocity profiles for θ=**60**^{o} using 100, 20, 10 and 4 lines. The thick line indicates the true velocity profile, the continuous line is the mean of the estimates, and the dotted lines are the standard deviations.

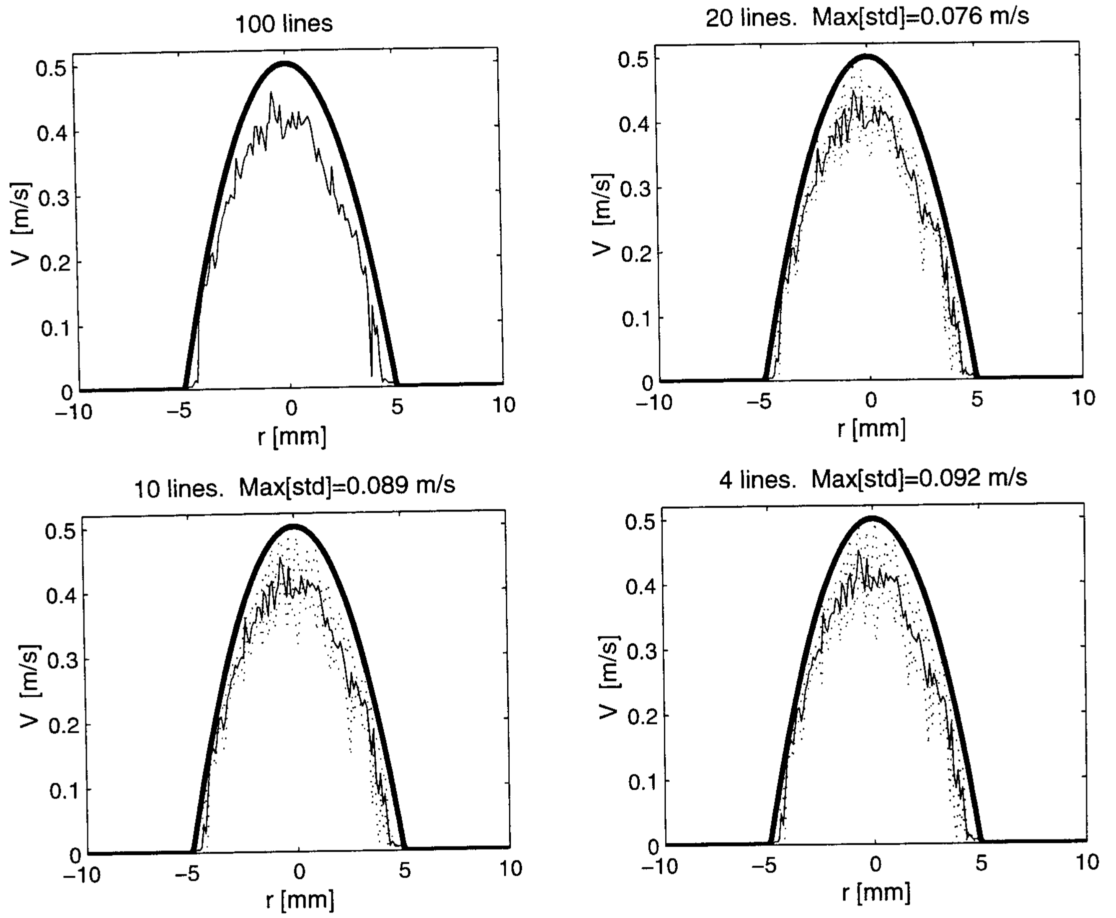

Figure 13: Estimated velocity profiles for θ=**90**^{o} using 100, 20, 10 and 4 lines. The thick line indicates the true velocity profile, the continuous line is the mean of the estimates, and the dotted lines are the standard deviations.

INTERNATIONAL SEARCH REPORT

Interi nal Application No
PCT/DK 00/00244

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01P5/00 G01F1/66

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01P G01F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

WPI Data, PAJ, EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 616 231 A (INSTITUT FÜR BIOMEDIZINISCHE TECHNIK UND MEDIZINISCHE INFORMATIK) 21 September 1994 (1994-09-21) abstract page 4, line 30 -page 5, line 7; figure 1	1,17
A	WO 98 00719 A (B-K MEDICAL A/S) 8 January 1998 (1998-01-08) abstract page 9, line 10 -page 13, line 4; figure 1	1-32
A	US 5 409 010 A (BEACH ET AL.) 25 April 1995 (1995-04-25) abstract column 13, line 36 -column 15, line 61; figure 10	1-32

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
10 August 2000	18/08/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Kempf, G

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INTERNATIONAL SEARCH REPORT

Information on patent family members

Intern. ›nal Application No
PCT/DK 00/00244

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
EP 616231	A	21-09-1994	AT	118897	T	15-03-1995
			AT	163770	T	15-03-1998
			DE	58909035	D	30-03-1995
			DE	58909833	D	09-04-1998
			WO	9004793	A	03-05-1990
			EP	0394428	A	31-10-1990
			US	5117692	A	02-06-1992
WO 9800719	A	08-01-1998	AU	3254897	A	21-01-1998
			EP	0909395	A	21-04-1999
US 5409010	A	25-04-1995	NONE			