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Acoustic velocity measurement by means of Laser Doppler Velocimetry: Development of an Extended Kalman Filter and validation in free-field measurement

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ABSTRACT

A signal processing technique, based on the use of an Extended Kalman Filter, has been developed to measure sound fields by means of Laser Doppler Velocimetry in weak flow. This method allows for the parametric estimation of both the acoustic particle and flow velocity for a forced sine-wave excitation where the acoustic frequency is known. The measurements are performed from the in-phase and the quadrature components of the Doppler downshifted signal thanks to an analog quadrature demodulation technique. Then, the estimated performance is illustrated by means of Monte-Carlo simulations obtained from synthesized signals and compared with asymptotic and analytical forms for the Cramer–Rao Bounds. Results allow the validity domain of the method to be defined and show the availability for free-field measurements in a large range. Finally, an application based on real data obtained in free field is presented.

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1. Introduction

The complete experimental determination of an acoustic field measure requires the measurement of both acoustic pressure and acoustic velocity. This enables an estimation of the acoustic intensity or impedance and gives much information about source radiation or acoustic energy exchange. Today, acoustic pressure can be measured easily with microphones. Acoustic velocity can also be measured, but velocity sensors are less common. Velocity measurement techniques can be divided into two families. The first, indirect methods, give an estimation of the particle velocity using at least two pressure measurements and a propagation model. The second, direct methods, give an estimation of the acoustic velocity using three major approaches of which the first is the hot wire anemometer [1], whose working principle has been described by de Bree [2]. This probe is calibrated using Laser Doppler Velocimetry (LDV) (see Section 2.1) in the frequency range (300 Hz; 4000 Hz) and in the velocity range (2.5 mm/s; 45 mm/s) [3]. Work concerning impedance or intensity measurements has been presented by Lanoye et al. [4] and by de Bree et al. [5]. The hot wire anemometer has also been used for very near field measurement close to a vibrating surface [6].

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Nomenclature	
\mathbf{A}_k	state transition matrix
\mathbf{C}_k	observation matrix
$\text{CRB}(V_{ac})$	Cramer–Rao Bounds for the estimation of V_{ac} ($\text{m}^2 \text{s}^{-2}$)
$\text{CRB}(V_{co})$	Cramer–Rao Bounds for the estimation of V_{co} ($\text{m}^2 \text{s}^{-2}$)
$\text{CRB}(\phi_{ac})$	Cramer–Rao Bounds for the estimation of ϕ_{ac}
D	sensitivity of the LDV set-up (kHz/m/s)
D_x	probe volume dimensions along \mathbf{x} -axis (m)
E	constant modulation amplitude
$E(k)$	Doppler signal discrete magnitude
$E(t)$	Doppler signal magnitude
F	ratio between SNR before and after quadrature demodulation
f_{ac}	reduced acoustic frequency
F_{ac}	acoustic frequency (Hz)
F_B	Bragg frequency (Hz)
F_c	cut-off frequency of the low-pass filters (Hz)
F_D	Doppler frequency (Hz)
F_{exc}	sine wave excitation frequency of the needle tip (Hz)
F_{max}	maximum frequency of $E(t)$ (Hz)
F_p	cut-off frequency of the photomultiplier (Hz)
F_s	sampling frequency (Hz); $F_s = 1/T_s$
G	non-linear function of the observation equation
i	distance between fringes (m)
k	sample index
K	coefficient related to the laser source power, the photomultiplier input voltage, the observation direction and the scattering efficiency of the particle
\mathbf{L}_k	gain matrix
M	term which accounts for the positive sign of the light intensity (pedestal)
N	number of samples
n_p	number of acoustic periods
N_p	number of acoustic periods inside the Doppler signal
N_{p0}	limit of convergence of the EKF
N_0	power spectral density
$\mathbf{P}_{k k-1}$	error covariance matrix
P_p	noise power at the output of the photomultiplier
\mathbf{Q}_k	process error covariance parameter
\mathbf{R}_k	measurement error covariance parameter
$\mathbf{R}_{V_{k,l}}$	measurement error covariance matrix
$\mathbf{R}_{W_{k,l}}$	process error covariance matrix
$s(t)$	Doppler signal
SNR	signal to noise ratio
SNR _p	signal to noise ratio at the output of the photomultiplier
t	time (s)
T_s	sampling period (s); $T_s = 1/F_s$
t_0	time at which the particle crosses the center of the probe volume (s)
\vec{v}	particle velocity
V_{ac}	acoustic velocity magnitude (m/s)
\hat{V}_{ac}	estimation of V_{ac} (m/s)
V_{co}	flow velocity (m/s)
\hat{V}_{co}	estimation of V_{co} (m/s)
\mathbf{V}_k	measurement error
v_x	projection of \vec{v} along \mathbf{x} -axis (m/s)
$v_1(k)$	discrete-time in-phase noise
$v_1(t)$	zero mean Gaussian noise (in-phase component)
$v_2(k)$	discrete-time quadrature noise
$v_2(t)$	zero mean Gaussian noise (quadrature component)
\mathbf{W}_k	process error
$x(k)$	discrete time location of the particle in the probe volume (m)
X_{ac}	acoustic particle displacement (m)
\mathbf{X}_k	state vector
$\hat{\mathbf{X}}_k$	state vector estimate
$x(k)$	discrete time location of the particle in the probe volume (m)
x_0	particle location in the probe volume when $t=0$ (m)
$x(t)$	particle location in the probe volume (m)
x_0	particle location in the probe volume when $t=0$ (m)
$x_1(k)$	first element of the state vector; $x_1(k) = \phi(k)$
$x_2(k)$	second element of the state vector; $x_2(k) = V_{ac} \cos \phi_{ac}$
$x_3(k)$	third element of the state vector; $x_3(k) = V_{ac} \sin \phi_{ac}$
$x_4(k)$	fourth element of the state vector; $x_4(k) = V_{co}$
\mathbf{Y}_k	observation vector
$y_1(k)$	discrete time Doppler signal in-phase component
$y_1(t)$	Doppler signal in-phase component
$y_2(k)$	discrete time Doppler signal quadrature component
$y_2(t)$	Doppler signal quadrature component
α	Doppler signal modulation level; $\alpha = DV_{ac}/F_{ac}$
β	related to the probe volume dimensions (m^{-1}); $\beta = 2/D_x$
$\Delta_C(k+1)$	state transition matrix depending on time variable
$\Delta_S(k+1)$	state transition matrix depending on time variable
$\varepsilon_{V_{ac}}$	estimation error for V_{ac} (%)
$\varepsilon_{V_{co}}$	estimation error for V_{co} (%)
$\varepsilon_{\phi_{ac}}$	estimation error for ϕ_{ac} (°)
θ	angle between beams (rad)
λ_L	laser wavelength (m)
σ^2	noise power; $\sigma^2 = \sigma_1^2 = \sigma_2^2$
$\sigma_{V_{ac}}$	standard deviation of V_{ac} (m s^{-1})
$\sigma_{V_{co}}$	standard deviation of V_{co} (m s^{-1})

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