Theoretical and Experimental Investigation of Effects of Flow Fluctuations on UDV Signals

Volkan Köseli, Yusuf Uludag
Department of Chemical Engineering, 06531 Ankara, Turkey

Effects of oscillating flows on the frequency spectrum of back-sampled pulsed ultrasound signals (PUS) are investigated both experimentally and theoretically. Simulation results revealed that while coherent component of velocity is encoded in the phase of the PUS, oscillating component is observed in terms of the amplitude and variance of the signal. The attenuation and variance increase on PUS spectrum in turbulent flow regime was also observed experimentally in measurements on a pipe flow system by means of DOP2125. Obtained PUS spectrums were closely related to the probability density function (pdf) of velocity at measurement point. The results indicate that ultrasound Doppler method can also be employed to determine turbulent flow characteristics such as time-averaged velocity, turbulence intensity and kinetic energy distributions in a pipe flow.

Keywords: Ultrasound Doppler Velocimetry(UDV), Discrete Fourier Transformation (DFT), Signal Attenuation, Pipe Turbulent Flow

1 INTRODUCTION

Pulsed Ultrasound Doppler Velocimetry (UDV) measurement technique is widely used in medical field for fluid flow measurements[1]. This technique is based on the velocity measurement using the phase of the successively recorded sound echo from a point through the spectral analysis of the signals. Here the main assumption is that velocity remains constant at least within the measurement time scales. Therefore UDV has mainly been applied for cases involving laminar flows[2]. In many applications, on the other hand, there are always small or large flow fluctuations[3]. These fluctuations can be expected to deteriorate the velocity measurement quality in ordinary UDV applications. Eliminating those negative effects and investigating the nature of the fluctuations themselves, such as turbulence, can be possible by understanding the impact of the flow fluctuations on the UDV signals quantitatively. A recent study about the intensity fluctuations of ultrasonic scattering in highly turbulent channel flow shows the potential of Doppler Ultrasound techniques for the investigation of turbulence[4].

Flow fluctuations that occur within the time scales of UDV measurement, i.e. from milliseconds to seconds, interfere with the regular build up of the signal phase. Typical time scales of the turbulence eddies in pipes also fall into this time interval. Therefore UDV can be potentially used as turbulence characterization probe in pipe flows. There are some studies in literature involving effects of the random motions on another technique, nuclear magnetic resonance imaging (NMRI). Signal attenuation due to random molecular motion[5-6-7] and effects of oscillating flow components on velocity profiles obtained by NMRI[8] have been reported.

The aim of the present study is to investigate the effects of the flow fluctuations on the UDV signal both theoretically and experimentally. The results obtain through analytical derivations and computer simulations are compared with those of the experimental measurements. In the following sections, the followed methodology and some of the obtained results are presented

2 SIMULATIONS

A computer code was written to obtain the spectrum and velocity values for several points by fast Fourier transformation of back-sampled PUS from particles in a pipe flow. Motion of particles was incorporated by tracking their position in the flow. The particles are assumed to have a velocity which was composed of a constant local value superimposed by an oscillating component with a specified amplitude and frequency (Eq. 1).

$$V(r) = U(r) + A_f \, Sin(w_f . t) \qquad (1)$$

For a measurement gate of distance of d_o from probe tip, the signal from measurement point having velocity without an oscillating part can be represented by;

$$S_n=A_o \mathrm{Sin}(2\pi f_o t_n) \quad (2)$$

where A is amplitude of PUS, f_o is emitting frequency and t_n is sampling time for n^{th} pulse. Discrete Fourier transform of these back sampled ultrasound signals will be;

$$S[k]=-\frac{A_o}{2} j(e^{j(a1+a2-a3)}N\delta[k-\frac{a_3N}{2\pi}]-e^{-j(a1+a2-a3)}N\delta[k+\frac{a_3N}{2\pi}]) \quad (3)$$

where $a_1=4\pi\frac{f_o}{c}d_o$

$$a_2=4\pi\frac{f_o}{c}\frac{d_o}{c}U_{|R-do|}\cos\theta$$

$$a_3=4\pi\frac{f_o}{c}U_{|R-do|}\cos\theta T_{prf}$$

N is total sampling number, θ is angle between pipe and probe

R is pipe radius.

and when $k=\frac{a_3N}{2\pi}$ (at Doppler frequency point)

amplitude of spectrum is;

$$\left|S[\frac{a_3N}{2\pi}]\right|=\frac{A_oN}{2} \quad (4)$$

and phase of spectrum is;

$$\mathrm{Arg}\{S[\frac{a_3N}{2\pi}]\}=4\pi\frac{f_o}{c}(d_o+U_{|R-do|}\cos\theta(1-T_{prf}))+\pi/2 \quad (5)$$

This shows that constant or coherent velocity only affects the phase of spectrum of PUS and has no effect on the amplitude. But random or oscillating velocity also affects the amplitude of spectrum as seen in simulation results. Spectrum taken from constant velocity flow point (Figure 1) and oscillating flow points with two different frequencies are presented (Figure 2 and 3) below. Simulations revealed the amplitude attenuation of PUS spectrums for oscillating type flow compared to laminar type constant velocity flow. This attenuation effect increases with increasing flow oscillation frequency and becomes less and less when flow oscillation period becomes much smaller than data acquisition period. However increasing amplitude of fluctuations always leads to a broadening and spectral energy spreading on spectrum.

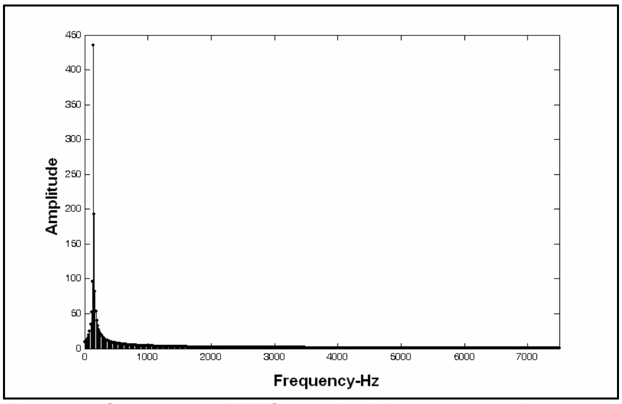

Figure 1: Spectrum of PUS received from center of pipe(ID=50mm) for velocity component in probe direction. Sampling frequency is 14346 Hz and sampling number is 1024. Local velocity is 78 mm/s without any fluctuation.

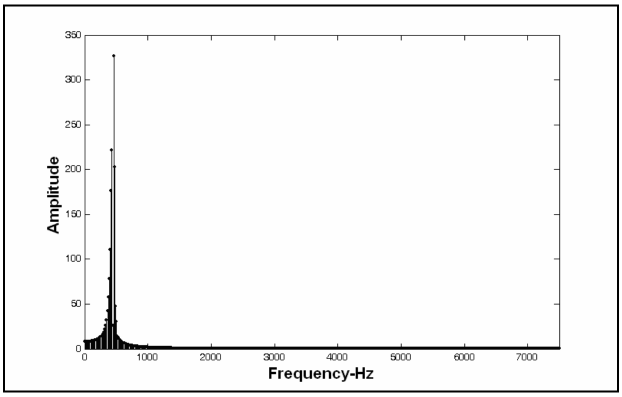

Figure 2: Spectrum of PUS received from center of pipe(ID=50mm) for velocity component in probe direction. Sampling frequency is 14346 Hz and sampling number is 1024. Local average velocity is 234 mm/s and it has an oscillating part with frequency 10Hz and amplitude 10% of the average.

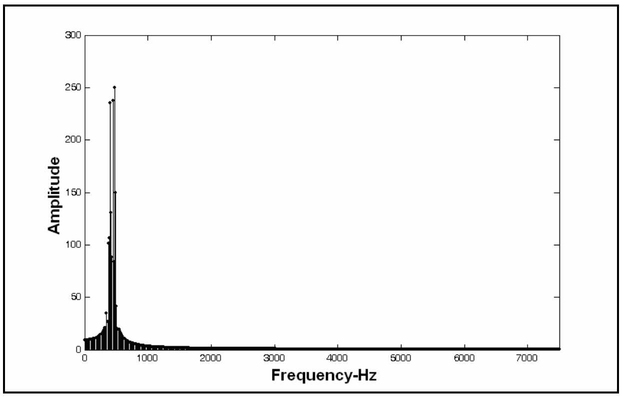

Figure 3: Spectrum of PUS received from center of pipe(ID=50mm) for velocity component in probe direction. Sampling frequency is 14346 Hz and sampling number is 1024. Local average velocity velocity is 234 mm/s and it has an oscillating part with frequency 20Hz and amplitude 10% of the average.

In Figure 4, it is clear that there is a complex relation between PUS amplitude and flow fluctuation. However one can observe a decreasing in PUS amplitude at high flow oscillation frequencies. But this behavior is not smooth. Amplitude of oscillating velocity component determines the period and frequency dependency (decreasing behavior) of this PUS amplitude attenuation. Flow oscillations distribute the total phase-shift information (caused by velocity) over a frequency interval in spectrum. This shows itself as an energy attenuation at frequency corresponding to average velocity value. If the flow oscillation period is shorter than total sampling period, signal attenuation becomes more pronounced.

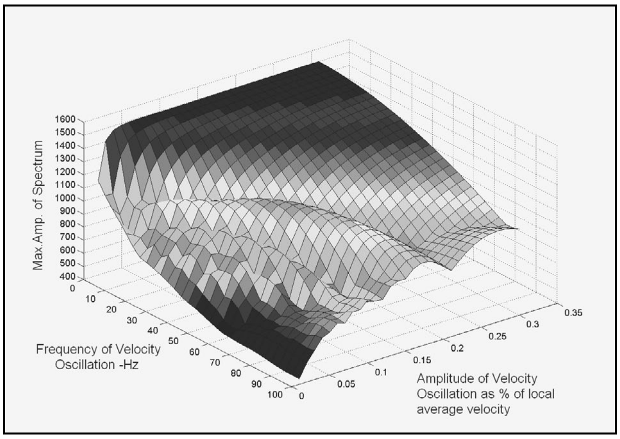

Figure 4: Change of maximum spectral amplitude P.U.S. with oscillating velocity components. Simulation parameters are: local average velocity is 0.234 m/s, , for the center of pipe with ID=50mm, Tpc (one profile measurement time)=0.2855 s (3.5 Hz).

3 EXPERIMENTAL MEASUREMENTS

Experimental measurements of velocity and spectrum were performed by means of a circulating flow system and DOP2125 Ultrasonic Doppler Velocimeter (Signal Processing, Switzerland). Measured values were taken for a gate of 25.9 mm away from pipe wall (pipe ID=46mm) and water flow for different Reynolds numbers. Tabulated velocities are velocity components of the flow which are parallel to the probe. Probe-pipe angle is 66^o. Results tabulated in Tab. 1

Standard deviation of spectrum increases with the Reynolds number. This is an expected result due to broadened probability density function (pdf) of velocity associated with the higher turbulence. Maximum amplitudes in spectrums were normalized by area under spectrum in order to eliminate the internal scaling of DOP2125. An exponential decreasing of this normalized maximum amplitude value with increasing turbulence effects is seen in accordance with simulation results (Figure 4).

4 SUMMARY

Effects of flow fluctuations on the UDV signals are investigated by means of both experimentally and computationally. According to the experimental results signal amplitude attenuation is the main effect on spectrum caused by oscillations. According to simulation results there is a complex relation between spectral amplitude and flow oscillation frequency. Experimental measurements confirmed the exponential type spectral attenuation caused by increasing oscillation frequencies which were obtained by increased Reynolds numbers. Also a broadening on spectrum of PUS was observed in experimental results. These broadening effects are closely related with probability density function of velocity for a real turbulent flow point. The results show that ultrasound Doppler velocimetry is a promising technique to study the turbulent flows.

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