

基于光声多普勒频谱标准偏差的自相关碳颗粒横向流速测量

卢涛,白薇薇

河南工业大学电气工程学院,河南 郑州 450001

【摘要】为了测量与超声探头信号接收轴线相垂直的碳颗粒悬混液的流速,采用多普勒频谱的标准偏差估计频带展宽,频谱标准偏差由自相关方法计算。光声信号由波长532 nm重复频率20 Hz的脉冲激光激励,由中心频率10 MHz的聚焦超声换能器采集。碳颗粒悬混液由微量注射泵驱动,时域光声信号经希尔伯特变换为复信号后进行自相关计算,多普勒频宽的标准偏差由若干序列A扫的自相关平均得到。对比之前基于序列A扫的互相关方法,所提出方法的优点是自相关中的信号时移大小可自定义,如时移量远小于信号扫描间隔,可避免信号混叠,避免互相关中对重复频率为数千赫兹脉冲激光的需求。该方法的可行性通过测量横向流速为5.0~8.4 mm/s的碳颗粒悬混液的频谱标准偏差得到初步验证,实验结果显示信号的自相关结果在测量范围内呈现线性分布趋势。

【关键词】光声多普勒;横向流速测量;频谱展宽;标准偏差;碳颗粒悬混液

【中图分类号】Q631

【文献标志码】A

【文章编号】1005-202X(2018)05-0598-04

Transverse flow velocity measurement of carbon particles based on photoacoustic Doppler standard deviation calculated with autocorrelation method

LU Tao, BAI Weiwei

College of Electrical Engineering, Henan University of Technology, Zhengzhou 450001, China

Abstract: In order to measure the flow velocity of carbon particle suspension perpendicular to the receiving axis of ultrasound transducer, the standard deviation of photoacoustic Doppler frequency spectrum which was calculated with an autocorrelation method was used to estimate the bandwidth broadening. A 532 nm pulsed laser with the repetition frequency of 20 Hz was used as a pumping source to generate photoacoustic signals which were then detected using a focused ultrasound transducer with a central frequency of 10 MHz. The suspension of carbon particles was driven by a micro-injection syringe pump. The photoacoustic signals in time domain were transformed into complex photoacoustic signals using Hilbert transformation before autocorrelation calculation. The standard deviation of Doppler bandwidth was calculated by averaging the autocorrelation results of several sequential A scans. Compared with the previously reported cross-correlation method based on sequential A scans, the advantage of the proposed method is that the time delay in autocorrelation can be customized. If the time delay was chosen much less than the time interval between the sequential A scans, aliasing can be avoided, moreover, the requirement for high laser repetition frequency up to several kHz in cross-correlation was avoided. The feasibility of the proposed method is preliminarily demonstrated by measuring the standard deviation of the carbon particle suspension with a transversal flow velocity from 5.0 to 8.4 mm/s. The experimental results revealed that the autocorrelation results were approximately distributed linearly within the measuring range.

Keywords: photoacoustic Doppler; transverse flow velocity measurement; bandwidth broadening; standard deviation; carbon particle suspension

前言

当脉冲激光照射诸如红细胞这类移动的光学吸

收介质时,所产生的光声信号的多普勒频移与流速成正比,称为光声多普勒效应。光声信号与常规多普勒超声相比具有较高的对比度和分辨率^[1-2]。光声多普勒流速测量包括对轴向和横向流速的测量。针对轴向流速的测量,可采用连续强度调制的激光为光声信号的激励源,多普勒信号采用锁相检测方法进行采集,通过短时快速傅里叶变换计算多普勒频移和轴向流速^[3-4]。在使用双脉冲激光器的轴向流速

【收稿日期】2017-11-18

【基金项目】河南省自然科学基金(162300410054);河南省属高校基本科研业务费专项(2015SRCJH13)

【作者简介】卢涛,博士,副教授,主要研究方向:光声成像与检测,E-mail: hautlutaotao@hotmail.com

测量中,通过时域互相关计算得到连续光声信号的时域偏移,根据光声信号对时域偏移和激光脉冲间隔计算光学吸收目标的轴向流速。在光声速度矢量中,流速的横向分量是必不可少的,当多普勒角接近 90° 时,光声多普勒频移大约为零,在超声和光学相干多普勒超声领域的研究已经证明使用多普勒带宽扩展来测量横向流速是可行的^[5]。频谱展宽可以通过多普勒频谱的标准偏差估计。此外,以往对光声多普勒效应研究已经证明,在横向流速测量中,可使用互相关方法计算光声多普勒频谱标准偏差^[6-8]。在这些研究中,需要重复率为几千赫兹的脉冲激光器,用来避免光声信号的混叠^[9]。然而,光声成像中常用的高功率脉冲激光器难以达到几千赫兹重复频率,并且流速的测量范围也受到连续扫描时间间隔的限制。

为了解决互相测量中信号扫描重复频率给测量带来的限制,借鉴光学相干多普勒测量中基于自相关的横向流速测量方法,将单次扫描信号的自相关计算与光声多普勒横向流速测量相结合计算信号的频谱展宽^[10-14]。光声多普勒频谱的标准偏差由若干序列A扫的自相关结果平均得到,信号自相关中的时移大小可自定义,当时移的大小小于信号扫描间隔时间即可避免信号混叠^[15-18]。在实验中,采用脉冲重复频率为20 Hz、波长为532 nm的脉冲激光作为光声信号激励源,光声信号由中心频率为10 MHz的聚焦压电换能器采集,该方法的可行性通过测量横向流速为5.0~8.4 mm/s的碳颗粒悬混液的频谱标准偏差得到初步验证,实验结果显示信号的自相关结果在测量范围内呈现线性分布趋势^[19-21]。

1 实验方法

在超声多普勒和激光多普勒测速中,有许多因素如速度梯度、湍流、布朗运动、斑点和通过超声探头聚焦区域的渡越时间都会展宽多普勒频谱。当流速较低时,悬混液中颗粒的布朗运动是频谱展宽的主要原因;当流速较高时,悬混液中运动颗粒通过超声探头聚焦区域的渡越时间是频谱展宽的主要原因。在光声多普勒中,可以忽略由激光入射角度引起的带宽展宽,当流速不太低时,多普勒带宽主要由移动的光学吸收颗粒穿过传感器焦点区域的时间决定,多普勒带宽 B_d 为:

$$B_d = \frac{4v \sin \theta NA_{\text{eff}}}{\lambda} + b \approx f_0 \frac{v}{c} W \sin \theta \quad (1)$$

其中, v 是流速, NA_{eff} 是聚焦超声波传感器的有效孔径, θ 是多普勒角度, f_0 是传感器的中心频率, W 和

F 是传感器的直径和焦距, c 是超声波传播速度, b 是布朗运动频谱的背景展宽,速度梯度和其他因素与流速无关。

标准偏差 σ 与多普勒频带之间的关系为:

$$B_{1/e} = 4\sigma \quad (2)$$

标准偏差 σ 由自相关运算得到:

$$\sigma^2 = \frac{2}{(\Delta T)^2} \left[1 - \frac{\left| \sum_{j=1}^n \tilde{I}_j \tilde{I}_j^*(\Delta T) \right|}{\sum_{j=1}^n \tilde{I}_j \tilde{I}_j^*} \right] \quad (3)$$

其中, ΔT 是自相关中的时移,和互相关不同, ΔT 可自定义,当 ΔT 远小于序列A扫间隔时,可避免信号的混叠, ΔT 的最小取值为采样间隔时间,实验中 ΔT 取值为 $0.5 \mu\text{s}$ 。信号 \tilde{I}_j 是时域光声信号 $I_j(t)$ 经希尔伯特变换后的复信号, j 为扫描次数,实验中由5次A扫自相关平均得到。由于照射激光为短脉冲激光, $I_j(t)$ 为宽带信号,希尔伯特变换前,信号首先通过低通滤波器以提高信噪比。滤波器定义为:

$$W(\omega) = \left(1 + \cos\left(\frac{\pi\omega}{\omega_c}\right) \right) / 2 \quad (4)$$

其中, ω_c 是10 MHz为上限的截止频率。

2 实验装置

实验系统构成如图1所示。图1采用波长为532 nm、重复频率20 Hz的Nd:YAG脉冲激光(Quanta-Ray INDI, Spectrum Physics)作为光声信号激励源,点聚焦压电超声换能器(Olympus IR-1008-S-SU)中心频率10 MHz、焦距19 mm、焦点直径0.23 mm。采用低噪声前置放大器(Olympus 5676)和数字存储示波器(Agilent 90404A)采集单帧光声信号。在自相关计算中使用5次序列的A扫。流体样品采用容积比为10%的碳颗粒悬混液,碳颗粒平均直径小于 $75 \mu\text{m}$ (C3345, Sigma-Aldrich),加入适量的聚钨酸钠(71913, Sigma-Aldrich)溶解于蒸馏水中。流体样品由微量注射泵(LSP01-1A, Longer pump, China)和10 mL注射器驱动,采用内径为0.95 mm的透明塑料软管作为模拟血管(Saint-Gobain Performance Plastics)。实验中预设流速范围为5.0~8.4 mm/s,速度增量0.2 mm/s。光声信号的采集如图1所示,其中 $\theta = 90^\circ$ 是多普勒角度, $I_j(t)$ 是时域光声信号, j 是扫描次数。

3 实验结果

5次序列A扫的时域光声信号如图2所示,不同流速设定下频带宽度的自相关计算结果如图3所示。从

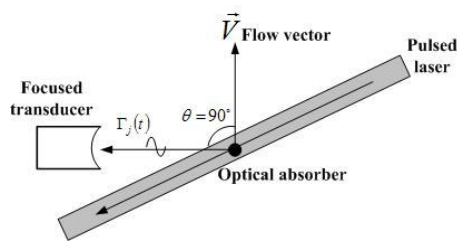


图1 实验方案

Fig.1 Experimental scheme

图3可以看出,当流速范围为5.0~8.4 mm/s,且速度增量为0.2 mm/s时,自相关结果大致与预设流速呈线性分布的关系。在互相关中,时移 ΔT 由激光重复率决定,为了让序列A扫的时域信号保持相关,在一定流速设定下,需要重复率较高的脉冲激光。在自相关中,单个A扫的时移可自定义,如果 ΔT 远小于序列A扫的间隔 T ,则可以避免频谱的混叠现象即不相关。 ΔT 的最小取值为信号的采样间隔 t_s ,在实验中, ΔT 的取值为 $0.5 \mu\text{s}$,该数值大于数据采样间隔 t_s 。

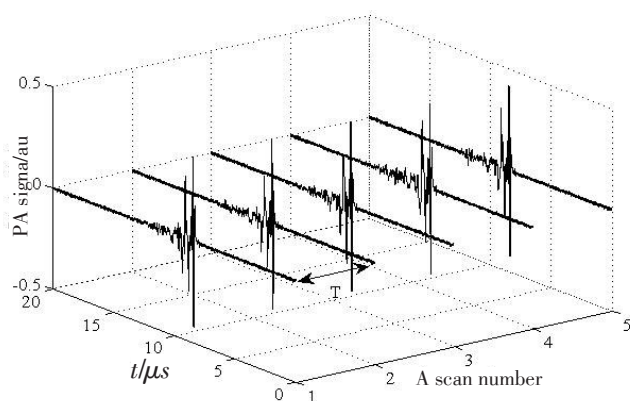


图2 时域序列A扫的光声信号

Fig.2 Photoacoustic signals in time-domain sequential A scans

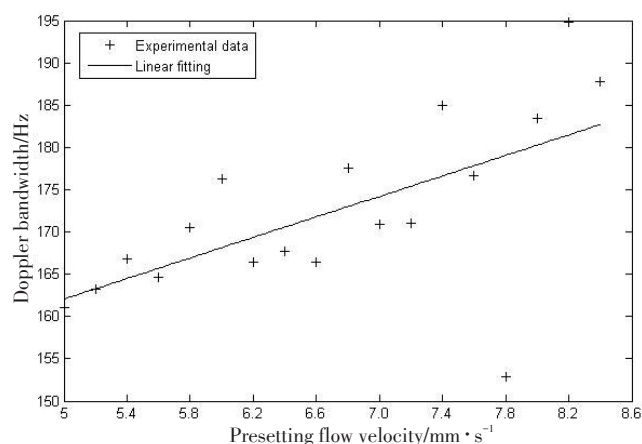


图3 自相关得到的不同光声多普勒信号频带宽度的标准偏差与拟合结果

Fig.3 Standard deviation of Doppler bandwidth calculated with autocorrelation method and its fitting results

然而在实验中,当预设流速低于5 mm/s时,自相关结果呈随机分布,分析其原因,应该是由于布朗运动、速度梯度和湍流等与流速大小无关的因素使多普勒频谱展宽所造成。如果传感器的焦点范围很小,速度梯度和湍流对频谱展宽所带来的干扰可相应地减小。在其他的研究中,利用高重复率的脉冲激光进行互相关运算,当使用焦点直径为 $27 \mu\text{m}$ 、超声传感器中心频率为75 MHz时,可测量的横向流速范围低于4.4 mm/s。此外,如果传感器的焦点非常小,那么在一定的激光重复率下,由于相关性减小导致可测流速的最大值也受限制。实验中,中心频率10 MHz超声换能器的焦点直径为0.23 mm,最小可测量的横向流速约为5 mm/s。测量的线性范围可以通过采用焦点直径更小的超声换能器和重复频率更高的脉冲激光进一步扩大。

4 结论

对使用自相关方法和频谱标准差的光声多普勒横向流速测量进行研究,初步验证了该方法的可行性。不同于互相关方法,自相关方法中的时移大小可自定义,因而避免了对高重复率脉冲激光的要求。在自相关中,理论上可测量的范围不受激光重复率和换能器的空间分辨率限制。实验中使用直径为几十微米级的碳颗粒悬混液作为模拟流体样品,测量流速为5.0~8.4 mm/s、速度增量为0.2 mm/s范围内的碳颗粒悬混液的横向流速。实验结果表明,自相关结果在所设定的测量范围内与预设速度之间呈近似线性分布。如果传感器的焦点直径较小并且激光重复率较高,线性度可以得到进一步改善。

【参考文献】

- [1] CAI Y, ARSAD N, LI M, et al. Buffer structure optimization of the photoacoustic cell for trace gas detection[J]. Optoelectron Lett, 2013, 9(3): 233-237.
- [2] ZHANG H F, MASLOV K, WANG L V. Photoacoustic Doppler flow measurement in optically scattering media[J]. Appl Phys Lett, 2007, 91(26): 4103-4105.
- [3] ZHANG H F, MASLOV K, WANG L V. Photoacoustic Doppler effect from flowing small light-absorbing particles[J]. Phys Rev Lett, 2007, 99(18): 4501-4504.
- [4] ZHAO Y, CHEN Z, SAXER C, et al. Doppler standard deviation imaging for clinical monitoring of *in vivo* human skin blood flow[J]. Opt Lett, 2000, 25(18): 1358-1360.
- [5] REN H, BRECKE K M, DING Z, et al. Imaging and quantifying transverse flow velocity with the Doppler bandwidth in a phase-resolved functional optical coherence tomography[J]. Opt Lett, 2002, 27(6): 409-411.
- [6] YAO J, MASLOV K I, SHI Y, et al. *In vivo* photoacoustic imaging of transverse blood flow by using Doppler broadening of bandwidth[J]. Opt Lett, 2010, 35(9): 1419-1421.

- [7] XU Y, WANG L V. Signal processing in scanning thermoacoustic tomography in biological tissues[J]. Med Phys, 2002, 28(7): 1519-1524.
- [8] BRUNKE J, BEARD P. Acoustic resolution photoacoustic Doppler flowmetry: practical considerations for obtaining accurate measurements of blood flow[J]. Proc SPIE, 2014, 8943: 89431K.
- [9] LAUFER J, DELPY D, ELWELL C, et al. Quantitative spatially resolved measurement of tissue chromophore concentrations using photoacoustic spectroscopy: application to the measurement of blood oxygenation and haemoglobin concentration[J]. Phys Med Biol, 2007, 52(1): 141-148.
- [10] ZHANG R, YAO J, MASLOV K I, et al. Photoacoustic Doppler axial flow measurement of homogenous media using structured illumination[J]. Proc SPIE, 2014, 8943: 89431U.
- [11] LU T. Photoacoustic Doppler flowmetry of carbon particles flow using an autocorrelation method[J]. Optoelectron Lett, 2014, 10(6): 467-469.
- [12] PIAO D, ZHU Q. Quantifying Doppler angle and mapping flow velocity by a combination of Doppler-shift and Doppler-bandwidth measurements in optical Doppler tomography[J]. Appl Opt, 2003, 42(25): 5158-5166.
- [13] KASAI C. Real-time two-dimensional blood-flow imaging using an autocorrelation technique[J]. IEEE Trans Ultrason Ferroelectr Freq Control, 1986, 33(1): 458-464.
- [14] YAO J, WANG L V. Transverse flow imaging based on photoacoustic Doppler bandwidth broadening[J]. J Biomed Opt, 2010, 15(2): 1304-1306.
- [15] ZHAO Y, CHEN Z, SAXER C, et al. Phase-resolved optical coherence tomography and optical Doppler tomography for imaging blood flow in human skin with fast scanning speed and high velocity sensitivity[J]. Opt Lett, 2000, 25(2): 114-116.
- [16] PIAO D, OTIS L L, DUTTA N K, et al. Quantitative assessment of flow velocity-estimation algorithms for optical Doppler tomography imaging[J]. Appl Opt, 2002, 41(29): 6118-6127.
- [17] PETROVA I Y, ESENALIEV R O, PETROV Y Y, et al. Photoacoustic monitoring of blood hemoglobin concentration: a pilot clinical study[J]. Opt Lett, 2005, 30(13): 1677-1679.
- [18] BRECHT H P, PROUGH D S, PETROV Y Y, et al. *In vivo* monitoring of blood oxygenation in large veins with a triple-wavelength photoacoustic system[J]. Opt Express, 2006, 15(24): 16261-16269.
- [19] WANG X D, KU G, WEGIEL M A, et al. Noninvasive photoacoustic angiography of animal brains *in vivo* with near-infrared light and an optical contrast agent[J]. Opt Lett, 2004, 29(7): 730-732.
- [20] WANG X D, PANG Y J, KU G. Three-dimensional laser-induced photoacoustic tomography of mouse brain with the skin and skull intact[J]. Opt Lett, 2003, 28(19): 1739-1741.
- [21] XU M H, WANG L H. Time-domain reconstruction for thermoacoustic tomography in a spherical geometry[J]. IEEE Trans Med Imaging, 2002, 21(7): 814-822.

(编辑:陈丽霞)