

Experimental verification of novel spectral analysis algorithms for Laser Doppler Anemometry data.

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Abstract

Two novel algorithms for estimating turbulence power spectra from Laser Doppler Anemometry (LDA) data, the *Refined sample and hold reconstruction (RR)* and the *Improved slot correlation (SC)*, have been tested on two test cases: grid turbulence and cylinder wake flow.

The algorithms were developed by Nobach et al. (1998), and van Maanen et al (1999) as a follow up on a benchmark comparison of some 15 algorithms reported by Benedict et al (1998). They were tested on simulated data generated from a known input spectrum, which was then used as a reference for evaluation of the algorithms.

In the present work, an experimental evaluation has been carried out, using reference spectra obtained with a Constant Temperature Anemometer (CTA), to evaluate spectra based on the RR, the SC and the traditional sample-and-hold reconstruction and resampling (S&H) algorithms.

It is shown, that RR and SC produce correct spectra up to frequencies above the data rate, whereas S&H, produces low-pass filtered spectra with a cut-off frequency corresponding to the data rate divided by 2π , the so-called the particle rate filter effect first reported by Adrian and Yao (1987). They recommended that data rates of 20 times the highest frequency of interest should be used for S&H.

The RR and SC thus have great relevance because they make it possible to obtain correct turbulence spectra at much lower data rates than with S&H. The practical implications of this are that less seeding is required, and that smaller lasers may be used.

Since RR is much faster than SC, and they produce very similar results, Dantec's LDA software has been extended with an on-line implementation of the RR algorithm.

The figure below compares the spectra obtained using CTA, and the RR, SC and S&H algorithms, for the cylinder wake flow.

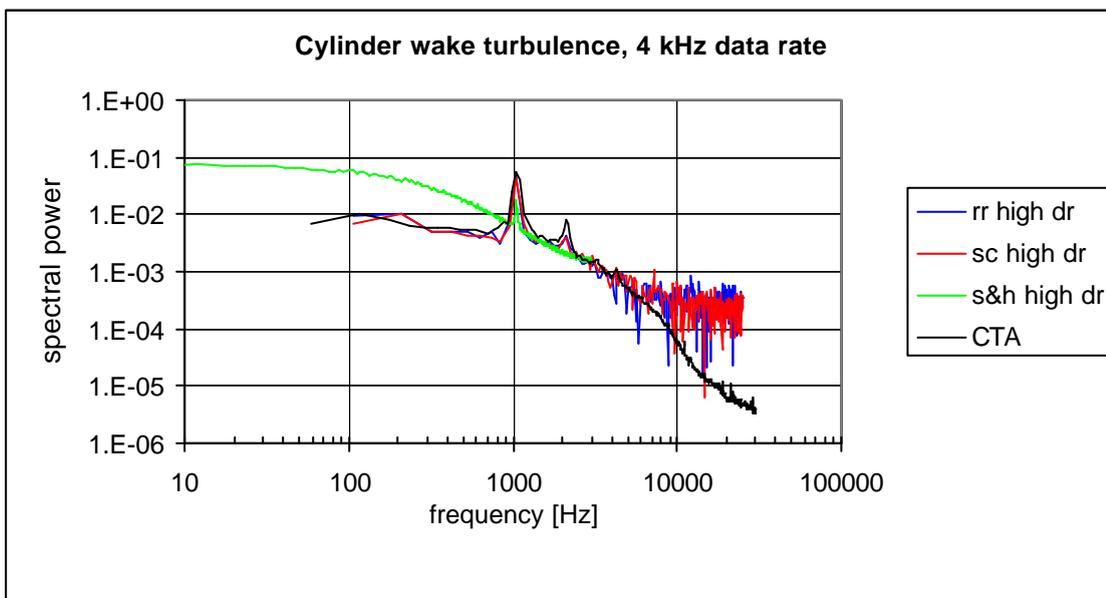


Fig. 1: Comparison of RR, SC and S&H LDA spectra with a reference CTA spectrum

Introduction

Measurement of turbulence spectra using the LDA technique has been a challenge for many years. The often used S&H algorithm suffers from the particle rate filter effect reported by Adrian and Yao (1987). They recommended a validated data rate of at least 20 times the frequency range of interest. The results presented in the present paper show that with SC and RR, a data rate of the same order of magnitude as the frequency range of interest is sufficient. This is of great practical importance, because in many cases it is impossible to inject enough seeding into a flow to obtain the very high data rates required for the S&H method.

Additional advantages of the new techniques are that there are no systematic errors at high frequencies (particle rate filter) or at low frequencies (aliasing errors). This prevents misinterpretation such as interpreting low pass filtered noise as a turbulence spectrum.

CTA is recognised as the reference for the measurement of turbulence spectra. For each test case, a CTA measurement was made in order to get a reference spectrum. Since the velocity signal from a CTA is continuous, equidistant sampling of the low-pass filtered signal and classical spectrum analysis using the Fast Fourier Transform can be used. The spectra produced from LDA data by the different algorithms can then be assessed by comparison with the CTA spectra.

In the literature, numerous algorithms for spectral analysis of non-equidistantly sampled velocity data have been reported. Some of the challenges are: signal reconstruction minimising bias and variance of the spectrum estimators, overcoming the effects of the particle rate low pass filter, and, not least, computing efficiency. RR is much faster than SC, so for the purpose of selecting a method for integration into LDA data processing software it is important to compare the results of the two.

This paper compares the results using

1. the RR algorithm
2. the SC algorithm
3. the S&H algorithm

All three were tested on high and low data rate data sets, and the results are compared with FFT processed CTA data from the same flows.

Two test cases were chosen to test different aspects:

Grid turbulence, which produces a broad band spectrum with a slope of $-5/3$ in the inertial subrange and a steeper slope in the dissipation range. CTA is capable of measuring this very well, but LDA spectra usually have the noise floor somewhere in the inertial subrange.

A *cylinder wake flow* has a pronounced peak in the turbulence spectrum due to vortex formation. The frequency of the peak can be predicted based on the Strouhal number. The cylinder dimension and flow velocity were chosen to produce this peak at 1 kHz. The tested data rates were 4 kHz and 0.4 kHz, i.e. above and below this frequency, in order to demonstrate the performance of the algorithms depending on the data rate.

Experimental set-up

The experiments were carried out in a closed loop wind tunnel. The test section had a cross section of 300×300 mm.

Two sets of measurements were carried out, in both cases using a free stream velocity of 30 m/s. The first set of measurements were made 133 mm downstream of a rectangular grid made of 1.5 mm diameter wire with a spacing of 6.5 mm.

The second set of measurements was made 26 mm downstream of a 6 mm diameter cylinder placed perpendicular to the flow direction. The Reynolds numbers are for both cases (based on grid spacing and cylinder diameter, respectively) about 12000. For each case, measurements were first made with CTA and then repeated with the LDA measuring volume positioned in the same position. For the LDA measurements the air was seeded with atomised droplets of glycerine with a size of approximately $2 \mu\text{m}$. The LDA consisted of Dantec two-component FiberFlow optics mounted on a two-axis traverse, two BSA enhanced processors, and BSA Flow Software. A 5 W Coherent Innova 90 Argon-Ion laser was used, running at 2 W (all lines). Only the 514.5 nm wavelength was used, measuring the velocity component in the main flow direction. The system was operating in back scatter mode.

The CTA was a Dantec StreamLine system. For grid turbulence, a 55P11 single wire probe was used. For the cylinder wake flow, a 55P61 X probe was used to resolve the horizontal and vertical velocity components, and the horizontal component was compared to the horizontal component measured by LDA.

Table 1 compares the measurement volumes of the LDA and CTA systems.

Table 1: measurement volume dimensions

LDA	CTA	
	55P11 probe	55P61probe
$2.5 \times 0.15 \times 0.15 \text{ mm}^3$	$1.2 \times 0.005 \times 0.005 \text{ mm}^3$	$0.8 \times 0.8 \times 1 \text{ mm}^3$

The hot-wire signal was passed through a signal conditioner with adjustable gain, offset and low pass filter cut-off frequency before being sampled using an A/D converter. Dantec StreamWare software controlled the A/D converter and converted the conditioned data to velocity data. The velocity data were processed using sample-and-hold reconstruction and FFT for the spectral analysis.

The same software was used to process LDA data, giving the possibility to compare the same algorithm (sample-and-hold reconstruction and FFT) on equidistantly sampled and non-equidistantly sampled data. The LDA data were also processed in a separate program, computing the spectrum based on the SC or the RR algorithms.

Results

Grid turbulence

Figs. 2 and 3 show RR, SC and S&H processed LDA data taken with 4 kHz and 0.4 kHz data rate respectively, with the CTA spectrum as reference.

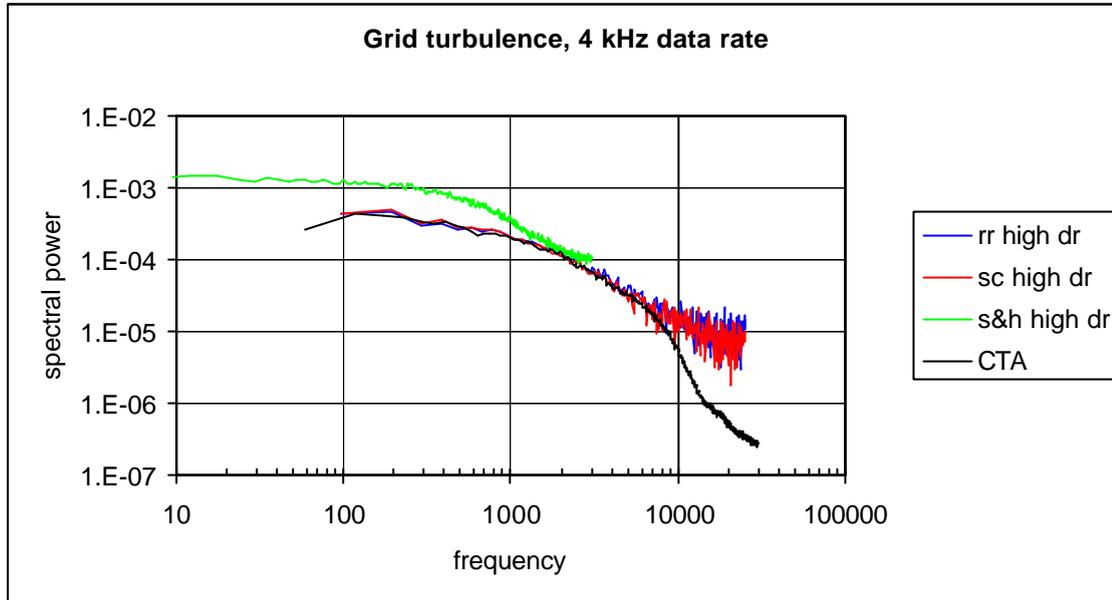


Fig. 2: Grid turbulence, 4 kHz data rate LDA spectra compared with CTA spectrum

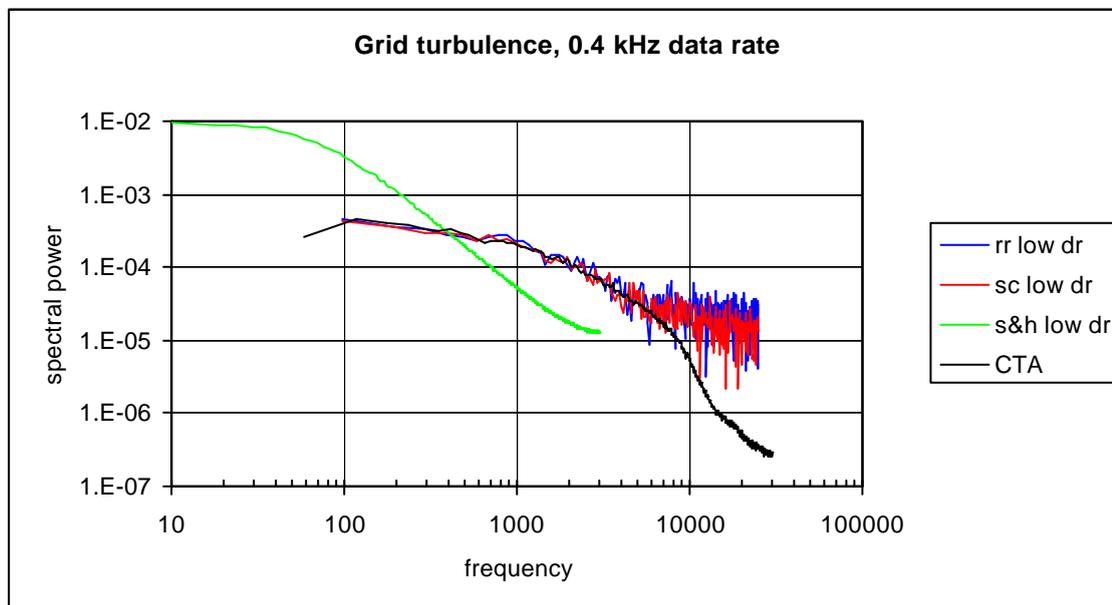


Fig. 3: Grid turbulence, 0.4 kHz data rate LDA spectra compared with CTA spectrum

The RR and SC spectra were based on 10 blocks of 100000 samples each. The S&H spectra were updated during acquisition, and were stable with 20000 or more samples. Therefore, the S&H spectra are based on 100000 samples.

The CTA data reveal both the inertial subrange and the dissipation range slopes.

The RR and SC spectra are in excellent agreement with the CTA till 5 to 6 kHz (4 kHz data rate) and till 3 to 4 kHz (0.4 kHz data rate). The RR spectra have slightly higher variance at high frequencies than the SC.

The S&H spectra are cut off from data rate/ 2π as described by Adrian and Yao. They also predicted that S&H would increase the energy content of the low frequencies as data rate decreases. This is clearly seen in the data.

Correct estimation of the turbulence spectrum using S&H would have required data rates of 100 kHz or more, which is often impossible in practice.

Comparison of 4 kHz and 0.4 kHz data rate for RR

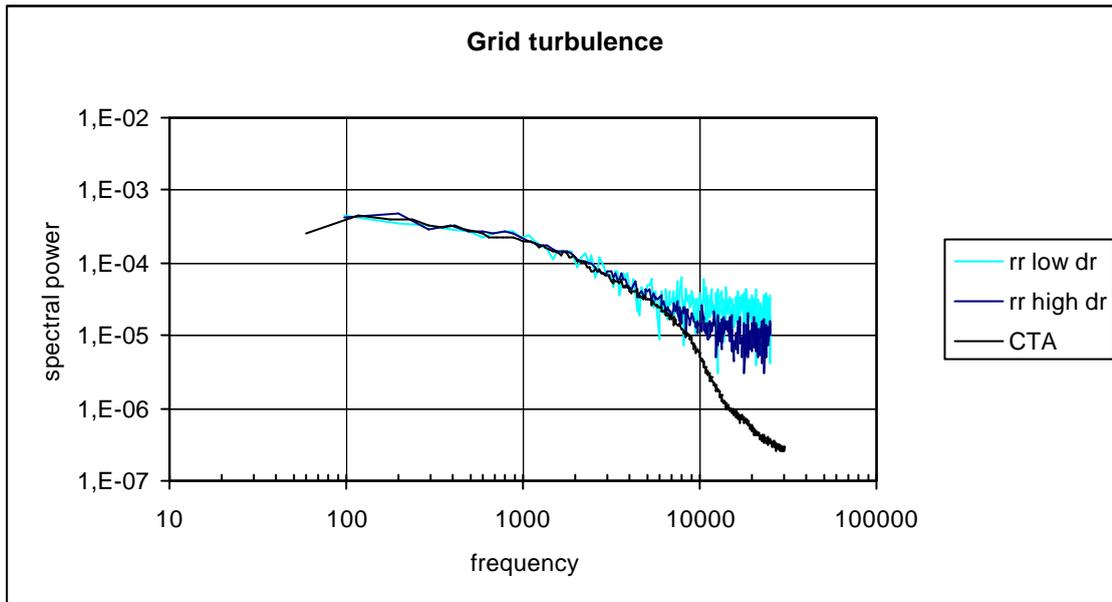


Fig. 4: Grid turbulence, 4 and 0.4 kHz data rate RR spectra compared with CTA spectrum

The comparison shows that the variance of the spectrum is higher for the low data rate case than for the high data rate case, and the noise floor is also higher. The SC shows the same characteristic.

Cylinder wake

Based on the Strouhal number the frequency of the vortex shedding behind the cylinder can be predicted to be 1000 Hz.

Figs. 5 and 6 show S&H, RR and SC spectra with 4 kHz and 0.4 kHz data rate respectively, with the CTA spectrum as reference.

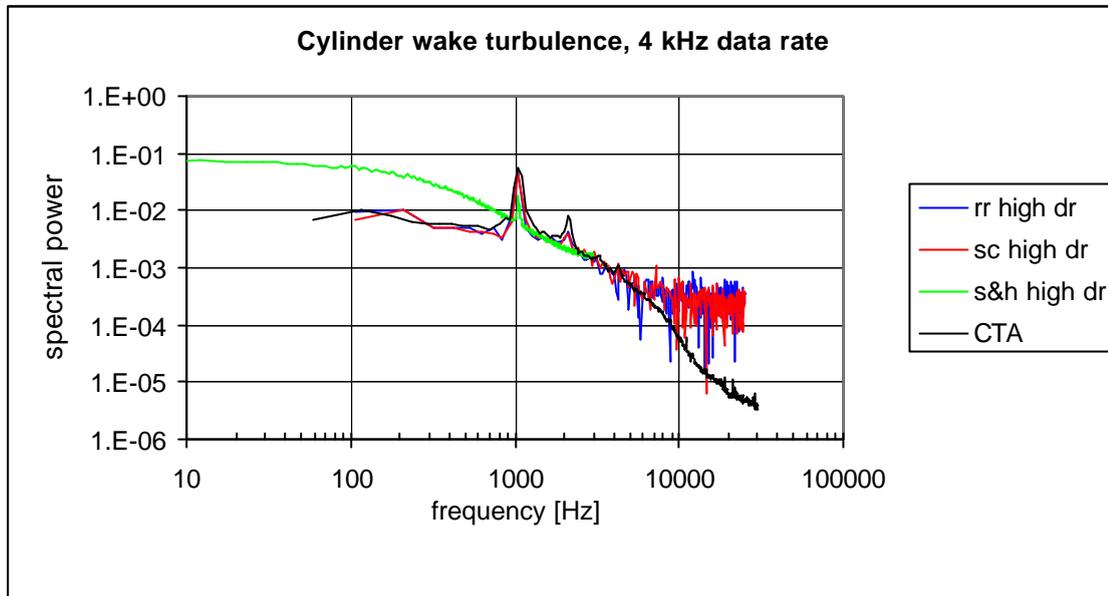


Fig. 5 Cylinder wake turbulence, 4 kHz data rate LDA spectra compared with CTA spectrum

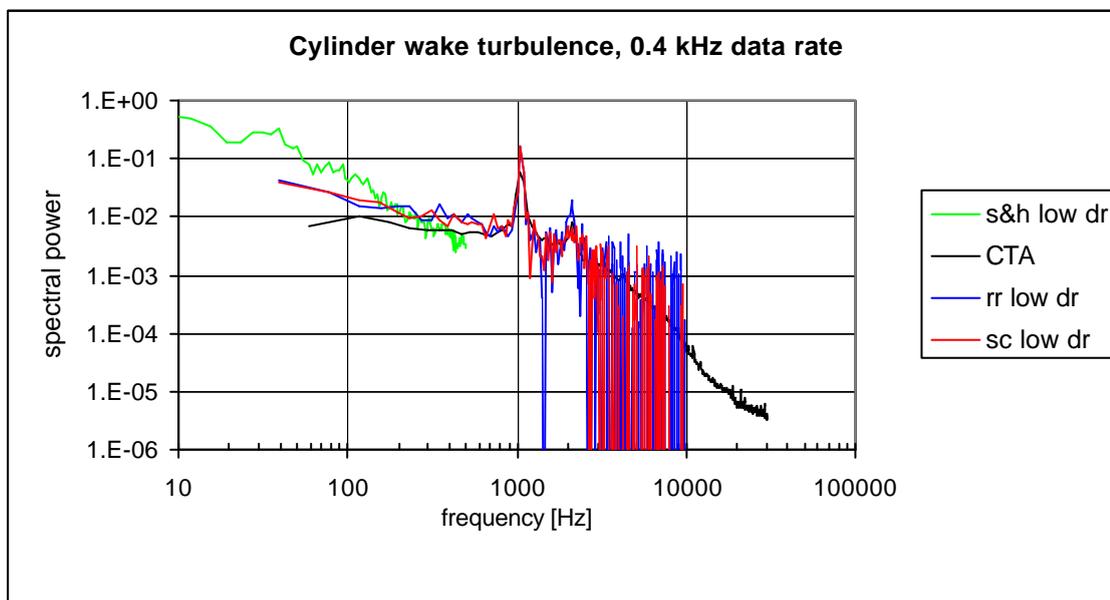


Fig. 6 Cylinder wake turbulence, 0.4 kHz data rate LDA spectra compared with CTA spectrum

The CTA data show two distinct peaks at 1 kHz and 2 kHz, corresponding to the vortex shedding frequency and a harmonic.

The RR and SC spectra capture these peaks both at high and at low data rate. For clarity, a graph zoomed in on the frequency range 100 to 10000 Hz for the low data rate case, is shown in fig. 7. It shows that the RR and SC overestimate the peaks compared to the CTA. This may be due to differences in the measurement volume size between the LDA and CTA systems, see table 1.

The S&H spectrum falls off due to the particle rate filter effect, captures the main peak (with data rate 4 kHz) but not the harmonic, and it shows too high energy at low frequencies.

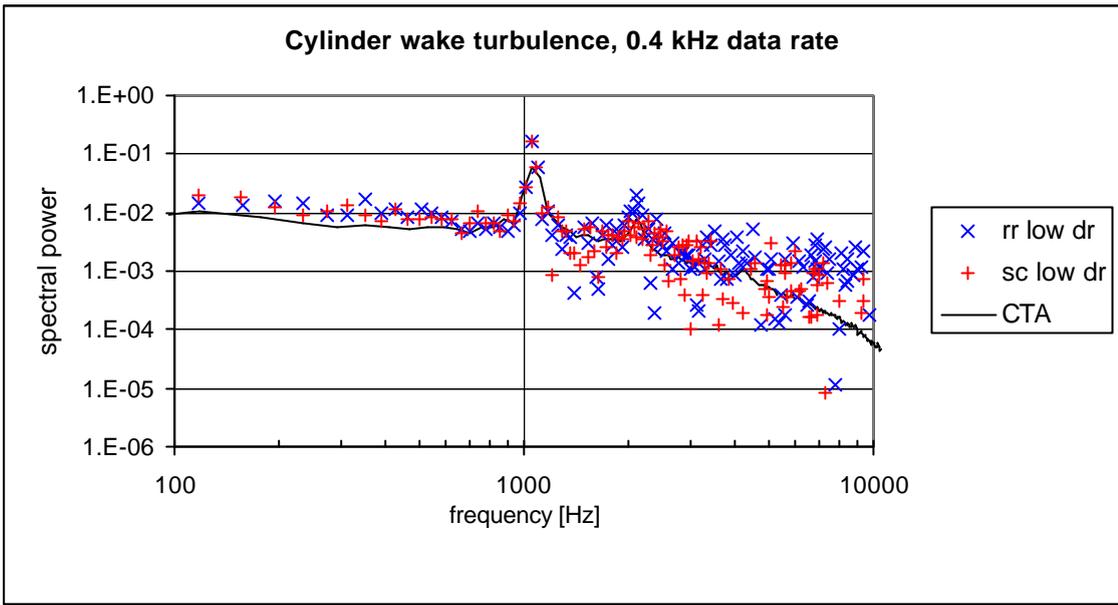


Fig. 7 Cylinder wake turbulence, 0.4 kHz data rate: frequency axis zoomed in on the peaks

Comparison of 4 kHz and 0.4 kHz data rate for RR

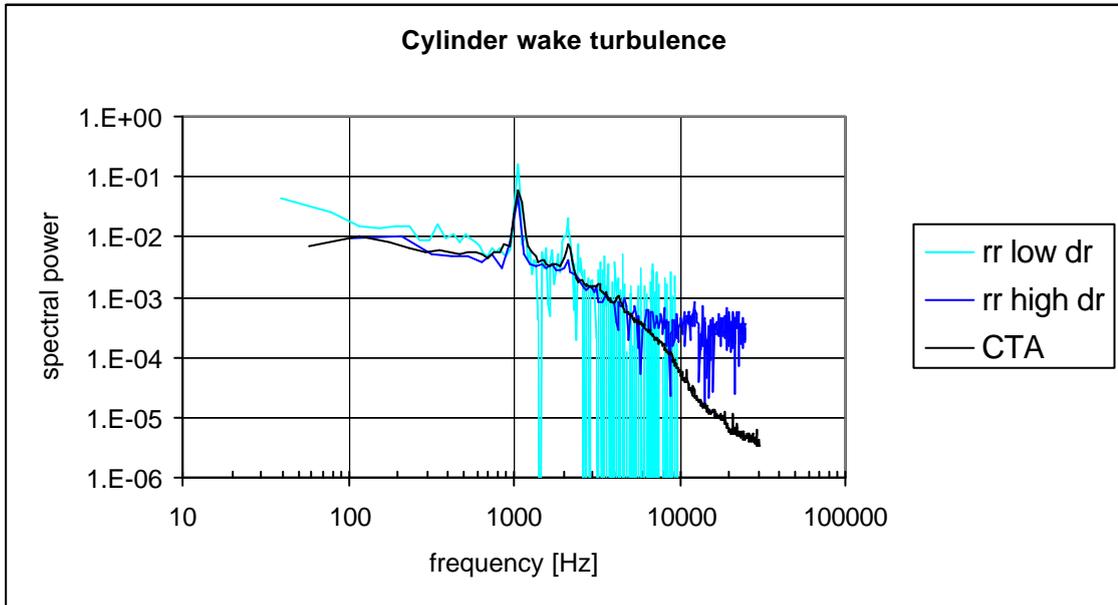


Fig. 8 Cylinder wake turbulence, 4 and 0.4 kHz data rate RR spectra compared with CTA spectrum

The high data rate spectrum agrees quite well with the CTA spectrum up to 4 to 5 kHz, after which the LDA spectrum reaches its noise floor.
 The low data rate spectrum has higher variance than the high data rate spectrum, and slightly overestimates the spectrum (but still performs much better than S&H, high data rate). It is important to notice that the spectrum is still reasonably good up to four times the data rate.
 The low data rate spectrum has its noise floor at a higher level than the high data rate spectrum, as expected.

Conclusion

It has been shown that the two new algorithms Refined sample and hold reconstruction (RR), and Slot correlation (SC), are well suited to compute turbulence spectra from LDA data. The required data rate is in the same order of magnitude as the frequency range of interest. The traditional Sample and hold and resampling (S&H) requires 10 to 20 times higher data rate to minimise the particle rate filter effect.

It has further been shown that RR produces results which are very similar to SC. Because RR is much less computation intensive, it is well suited for on-line data analysis during experiments. Dantec has therefore implemented this algorithm in its LDA data analysis software.

The two reported test cases have most of their energy content in the frequency range up to 10 kHz. Data rates in this range can be obtained experimentally in most cases. The traditional method requires at least 100 kHz data rate to cover the same frequency range, which is difficult to obtain in practical experiments.

References

Adrian, R. J. and Yao, C.S.: Power spectra of fluid velocities measured by laser Doppler velocimetry. *Exp. in Fluids*, 5:17-28. 1987

Benedict, L. H., Nobach, H. and Tropea, C.: Benchmark tests for the estimation of power spectra from LDA signals. *Proc. 9th Int. Symp. on Appl. of Laser techn. to Fluid Mechanics*, Lisbon, Portugal, Paper 32.6. 1998.

Nobach H, Müller E and Tropea C: Efficient estimation of power spectral density from laser Doppler anemometer data. *Experiments in Fluid* vol. 24, no 5/6, pp. 499-509. 1998

Van Maanen, H.R.E., Nobach, H., and Benedict, L.H.: Improved estimator for the slotted autocorrelation function of randomly sampled LDA data, *Meas. Sci. Technol.* 10, L4-L7. 1999.