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Signal Processing Technique for Boundary-Layer Measurements with a Laser-Doppler Velocity-Profile-Sensor

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Abstract

A new signal processing technique is introduced for the measurements with a laser-Doppler velocity-profile-sensor. The new technique enables measurements in turbulent boundary layers, which was not possible with a former processing technique. It was realized in an offline method, which processes the recorded signals afterward data acquisition. It detects each Doppler signal with wide range of velocity using adaptive time-window and dynamic filtering techniques. Several validation conditions were included in order to reduce low quality signals and outliers. The developed technique was applied to real measurement data acquired in a boundary layer of a fully developed turbulent flow. It was demonstrated that the new technique effectively processes measurement signals in a turbulent boundary layer.

1. Background

Flow velocity near the wall is important for fundamental research and applications in fluid mechanics. In turbulent flows it is desired to investigate flows with a high spatial resolution to resolve the fine scale in turbulence. Recently developments of direct numerical simulation provided detailed information on the structures of turbulent flows (Moin and Mahesh 1998), but their applications are still limited to flows with moderate Reynolds number. Comparative experimental investigation is desired to make reliable data base and to validate numerical simulations.

Laser Doppler anemometry (LDA) is one of the most widely used measurement techniques in turbulent flow research (Albrecht et al. 2003). It has an advantage of non-intrusiveness but its spatial resolution is limited because of the spatial averaging effect in the finite size of the measurement volume. The effect becomes severe where there is a steep velocity gradient or the flow scale of interest is smaller than the size of the measurement volume.

In order to overcome this shortcoming, a laser-Doppler velocity-profile-sensor has been proposed for flow measurements with a high spatial resolution (Czarske 2001). The sensor provides information of position as well as the velocity of a tracer particle passing through the measurement volume. It has a spatial resolution inside the measurement volume in the direction of the optical axis, and hence the spatial averaging effect is avoided in the direction. The velocity-profile sensor was successfully applied mainly to laminar flows (Czarske et al. 2002).

It has been continuously refined towards applications in turbulent flows, and one of the main goals is the near-wall measurement in turbulent boundary layers. For boundary layer measurements with a conventional LDA, the measurement volume is placed with its longitudinal axis parallel to the wall surface (Fig. 1(a)). This reduces the spatial averaging caused by the finite size of the measurement volume in a steep velocity gradient. In contrast, the measurement volume of the velocity-profile sensor is adapted to the flow with its lateral axis perpendicular to the wall (Fig. 1(b)). This arrangement is used for having higher spatial resolution in the direction where a steep velocity gradient exists. It indicates, on the other hand, the longitudinal direction of the measurement volume is placed in the direction of the steep velocity gradient. Therefore wide range of particle velocity occurs in the measurement volume (Fig. 2), which is caused by steep mean velocity gradient as well as turbulent fluctuation. This wide range of velocity made it difficult to apply the signal-processing technique used for the former measurements with the velocity-profile sensor.

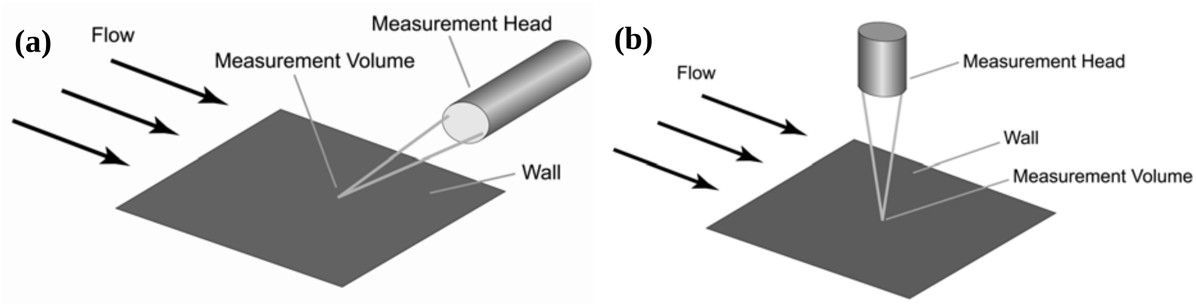

Fig. 1 Different arrangements of velocity measurements in a turbulent boundary layer close to the wall. (a) with a conventional LDA, (b) with a velocity-profile sensor.

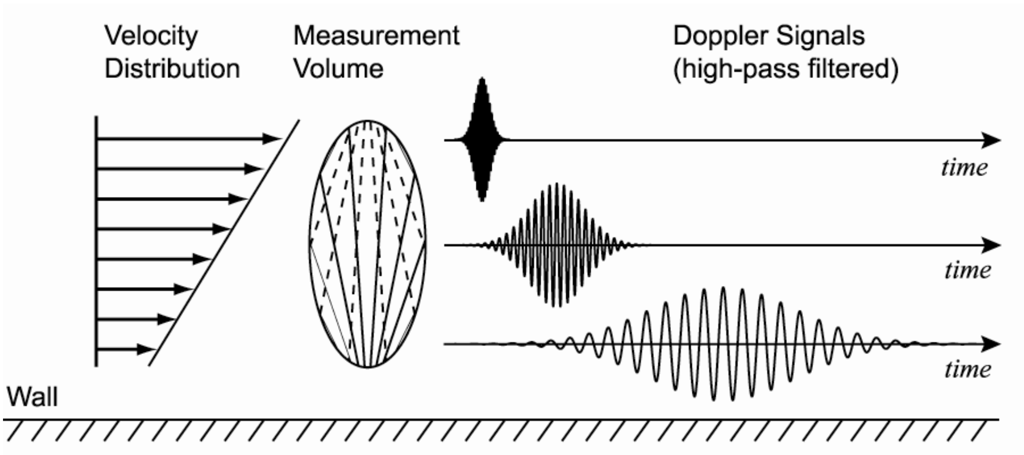

Fig. 2 Schematic features of Doppler signals in a turbulent boundary layer with a velocity-profile sensor. Due to the long size of the measurement volume in wall normal direction and steep velocity gradient, tracer particles with very wide range of velocity randomly passes through the measurement volume.

We have developed a new technique to process the measurement signals of velocity-profile sensor in turbulent boundary layers. In contrast to the former works, the measurement signals are processed with adaptive time-window and dynamic filtering techniques. Software was developed to detect each Doppler signal from wide range of velocity recorded during flow measurements. Detected signals are processed with detailed validation conditions to remove erroneous information. This technique enables the signal processing of the flow measurements in the near-wall region, which was not possible by the former signal-processing technique. We describe the overview of the processing technique, and show the real measurement results processed with the former technique and with the new technique proposed in the present work.

2. Concept and Realization

The signal processing for velocity-profile sensor mainly consists of two parts: signal detection and evaluation. Especially the former one is important for the signal processing of the velocity-profile sensor, whilst the latter one is a straightforward extension of the FFT-based signal processing used for conventional LDAs. The signal processing includes also several validation conditions to exclude low quality signals and outliers. First, the problems of the former processing technique are briefly overviewed to introduce the necessity of the new technique. Then the details of the new technique will be described with respect to the detection, evaluation and validation.

2.1 Former technique

In the former works a signal was triggered and digitally acquired with a certain fixed numbers of sample points. The group of the acquired sample points was simply regarded as a single detected signal and it was processed accordingly. This way of signal processing is valid for the measurements of a flow with a small velocity fluctuation or/and with a moderate mean velocity gradient compared with the length of the measurement volume. It properly detects signals when the signal duration fits to the set acquisition length (Fig. 3 middle). However, it fails for the measurements of a flow with a large velocity fluctuation and/or with a steep mean velocity gradient inside the measurement volume. In such a measurement condition, wide range of velocity exists and the duration of a signal changes drastically depending on the particle velocity (reversely proportional to the velocity). There are two typical cases, in which former way of signal processing fails. Here we consider such two extreme cases of particle velocity: very high velocity (Fig. 3 top) and very low velocity (Fig. 3 bottom).

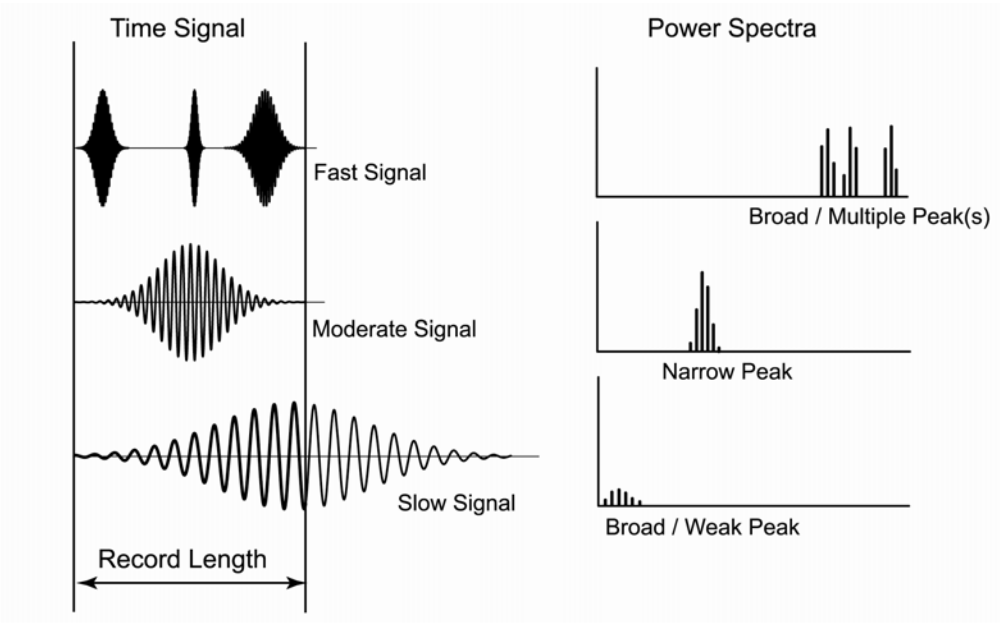

Fig. 3 Illustrations of typical Doppler signals of velocity-profile sensor with respect to the fixed record length of data acquisition. (left-hand side: time signal, right-hand side: power spectra)

In the first case, the velocity is very high and the signal duration is only a very small part of the acquired data length. If the duration of a signal is very short compared to the record length (not shown in Fig. 3), the signal-to-noise ratio (SNR) decreases and hence the signal is not validated. In another case, if there exist multiple burst signals within a single record length (Fig. 3 top), all the signals inside the record are treated as a single burst and hence the power spectrum of the signal results in multiple peaks or a broad shape. (The peak frequencies are normally not identical because the velocity of each particle is statistically randomly distributed.) As a consequence such a signal is simply discarded as a non-validated signal because of its low signal quality. Typically it happens when the record length is set to be long in order to detect low velocity signals. The authors observed many of such signals were not validated even when the individual signal had a good enough quality during measurements. The second case is for a very slow velocity particle, which has a signal duration longer than the acquired data length (Fig. 3 bottom) and it is truncated. In this case the power spectrum shows a broad shape because of the small numbers of cycles in the data length. Therefore, the signal is discarded by the low signal quality. This occurs when the data length is not set to be long enough to record a signal of lowest velocity in the flow.

For the measurements in the near-wall region of a turbulent boundary layer, the range of velocity distribution becomes broad and therefore the way of using a fixed record length fails to detect signals in the whole velocity range. This can also happen to the measurements with a conventional LDA but it is not critical due to the measurement arrangement (Fig. 1 (a)). A solution for compensating this effect was proposed by Durst et al (1998). However, for measurement in turbulent boundary layers with velocity-profile sensor, the effect is more prominent due to the measurement arrangement (Fig. 1 (b)). With the former signal processing, many good quality signals were discarded and therefore the validation rate remained very low.

2.2 New technique

Our strategy for solving the detection problem is to set the data acquisition length long enough to detect the slowest velocity signal and then to detect each signal with adaptive time-window technique (Fig. 4). By setting the acquisition length long enough, no information is lost for a signal with a long duration. On the other hand, short duration signals are detected by applying adaptive time windows.

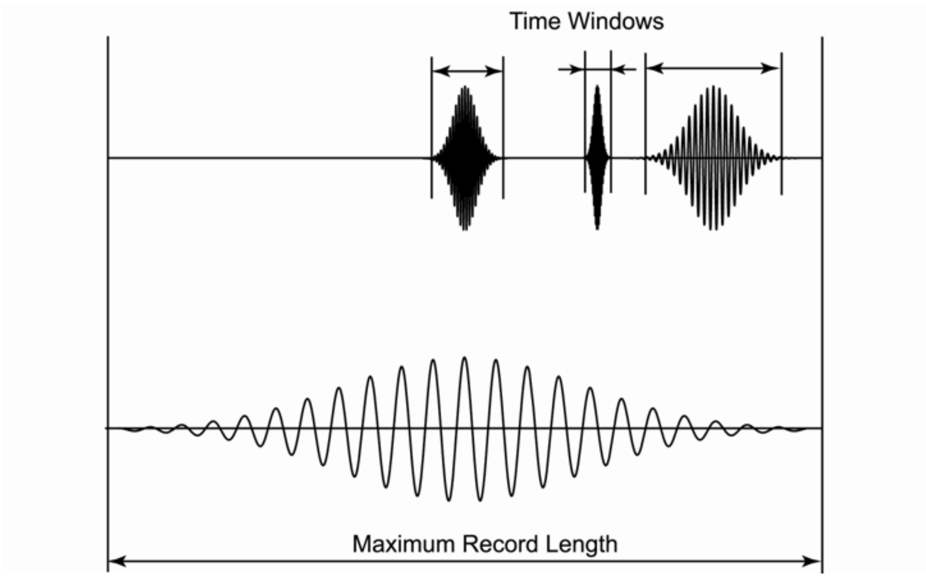

Fig. 4 Strategy of the new processing technique (Set the record length at maximum and record all the triggered signals during a measurement. Each signal is extracted by applying adaptive time window afterwards.)

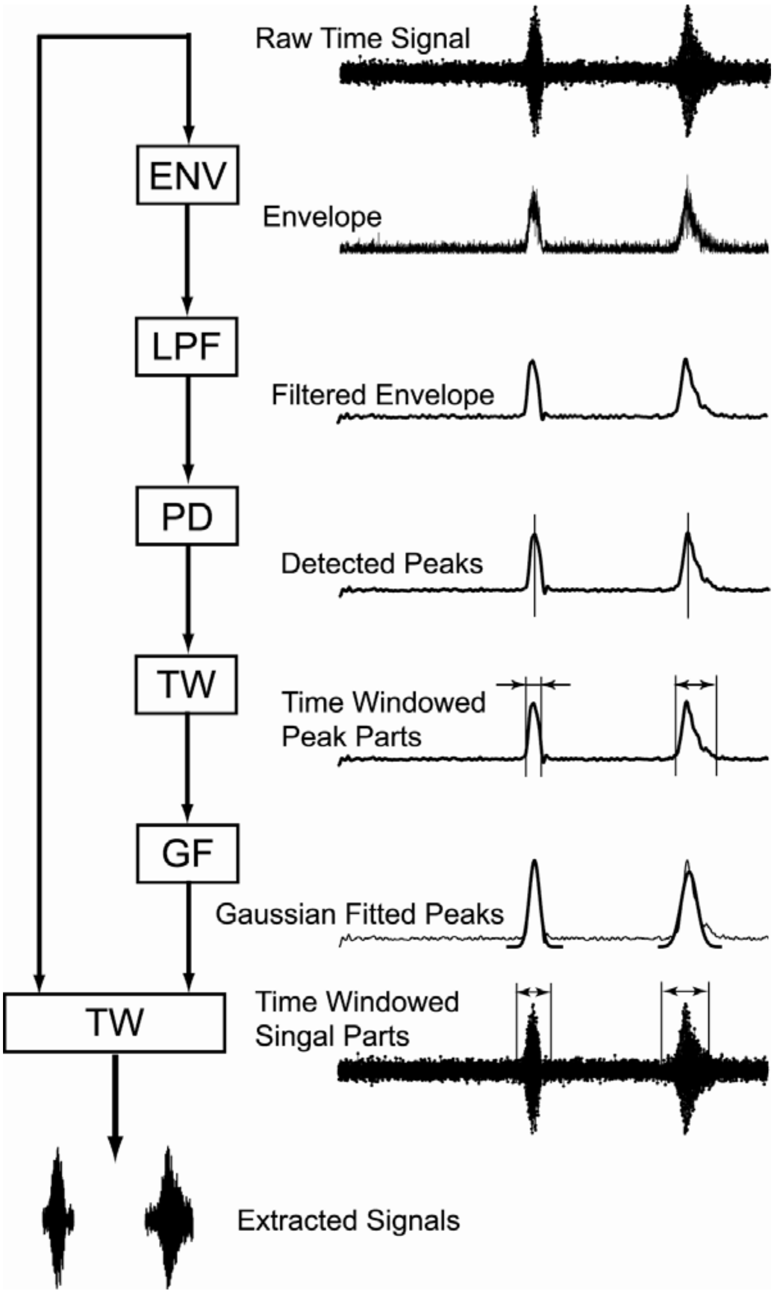

Fig. 5 Detection part of the signal processing. Real measurement signal with two bursts inside one record is shown with each processing step. (ENV: ENvelope Detection, LPF: Low-Pass Filter, PD: Peak Detection, TW: Time Window, GF: Gaussian Fit)

All the process was realized in a program written in MATLAB, and signals were processed afterward the measurements with the new technique. In the present work the technique was realized in an offline method because of the long processing time for detection and evaluation.

Fig. 5 shows the schematic diagram of the detection part together with a real measurement signal. Input is the raw time signal recorded in measurements. As a first step the envelope of the signal is calculated by using Hilbert transform. The envelope was low-pass filtered to suppress high frequency noise. Peak detection is applied for the low-pass filtered envelope to detect the signal part. From the peak detection each signal part is roughly extracted and Gaussian fit is applied to each extracted part. From the Gaussian fit more accurate peak-width is detected and it is used for extracting each signal part from the raw time signal. These procedures are conducted for the raw signals in both channels. Then the most probable signal pairs in the two channels are determined. The detected individual signal pair is extracted by applying a time window, and processed for the data evaluation described in the following subsection.

(b) Evaluation

The detected individual signal pair is processed for the evaluation of the position and the velocity. Fig. 6 illustrates the diagram of the evaluation part. First, the cut out signal pairs are band-pass filtered. The cut-off frequencies are dynamically determined by the signal durations which were estimated in the detection stage. This procedure reduces mainly high frequency noises and improves the signal quality. The band-pass filtered signal pair is zero-padded for the efficient calculation of FFT in the next step. Then the power spectrum of each signal is calculated and the Doppler frequency is estimated with a Gaussian fit using three maximum points in the power spectrum (Shinpaugh et al. 1992). From the Doppler frequencies, the position and velocity of the particle are calculated by using the calibration information.

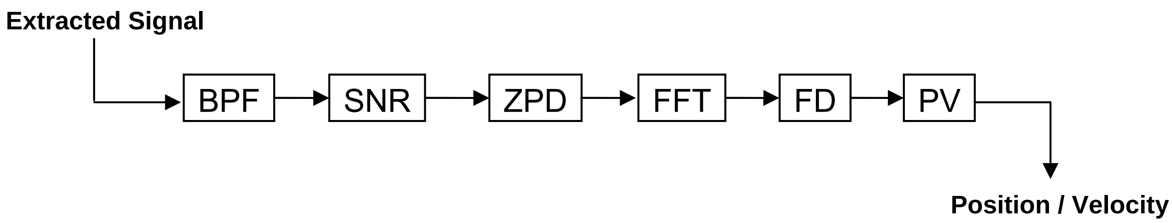

Fig. 6 Evaluation part of the signal processing. (BPF: Band-Pass Filter, SNR: Signal-to-Noise Ratio, ZPD: Zero PaD, FFT: Fast Fourier Transform, FD: Doppler Frequency estimate, PV: Position and Velocity calculation)

(c) Validation

Validation conditions were included in the signal processing in order to reduce low quality signals and outliers. Table 1 shows the conditions used for the processing. Only the signals satisfying all the validation conditions were used for reproducing the velocity profile afterwards. The conditions 3 to 7 listed in the Table 1 were used in the former signal processing technique too. Each validation condition is explained in the following.

Table 1. Validation conditions used for the present system

Validation 1, 2	Envelope peaks detection
Validation 3, 4	Signal-to-noise ratios
Validation 5, 6	Peak heights of power spectra
Validation 7	Calibration range
Validation 8	Velocity coincidence for both channels

Envelope peaks detection (validation 1, 2)

In the peak detection stage, the numbers of detected peaks, peak widths and the distance of neighboring peaks are calculated with Gaussian fit. The information is used to avoid detecting shot noise and too closely located signals. For each channel it is checked whether peaks are detected or not in the low-pass filtered envelope. If no peak higher than set threshold level is detected in either of two channels, it is regarded as no signal is detected in the time record and the record is skipped without any further processing.

SNRs (validation 3, 4)

The SNR is calculated for examining the quality of each signal. The calculation is based on the auto-correlation function. Only the signal pair with higher SNR than the set value is passed by this condition. Monitoring SNR is important since it has an influence on the estimation accuracy of Doppler frequencies (Albrecht et al. 2003) and hence the position/ velocity measurement of the velocity-profile sensor (Czarske et al. 2002).

Peak heights of power spectra (validation 5, 6)

The peak-height of each power spectrum is checked for determining the signal power. The signals with lower peak height than a preset threshold in the power spectrum were rejected in this condition. As well as with SNR this condition was included for eliminating signals with low quality.

Calibration range (validation 7)

The estimated particle position is checked if it is inside the range of the calibration conducted before the measurement. Only the signal within the calibration range is allowed to pass this condition. This prevents the signal from particle passing outside of the measurement volume.

Velocity coincidence for the both channels (validation 8)

The velocity calculated in both channels should be matched from the principle of the sensor. However, in practice, the calculated velocities do not match always in flow measurements. This was possibly caused by non-coincident signal pairs: signal in each channel originates from different position in the measurement volume with respect to the optical axis. Therefore this condition is necessary to supplementarily avoid unwanted outlier signals.

3. Processing Results and Discussion

The new processing technique described above was applied to real measurement data. The measurement was conducted in the near-wall region of the turbulent boundary layer in a fully developed two-dimensional channel flow. A fiber-optic velocity-profile sensor based on a frequency-division multiplexing (FDM) technique was used for the measurement. The details of the flow measurements and sensor setups are described in another paper in GALA 2005 (Shirai et al. 2005). Fig. 7 shows the results processed with the former and new technique respectively. The former technique has neither adaptive time-window nor dynamic filtering technique. For comparison same sets of the measurement data were used and same validation conditions were applied (SNRs, peak heights of power spectra, calibration range, velocity coincidence). The data was acquired in the Reynolds number of 1.8×10^4 (based on the bulk mean velocity and channel full width) and consists of about 40000 sets of signal records. Fig. 7 (a) is the processed result with former technique and (b) is the result with new technique. Each point indicates the average of 200 neighbor points. In the former processing (Fig. 7 (a)), the validation rate (ratio of numbers of validated signal to total detected numbers of signal) was less than 5 % out of the measured data close to the wall. On the other hand, more than 50 % of the detected signal was validated throughout the measurement data with the new technique (Fig. 7 (b)). This indicates that the adaptive time-window technique effectively detects the each signal and hence the validation rate was increased in the evaluation stage. Multiple burst signals in each set of a single record were successfully processed in most cases. Such an example is shown in Fig. 5. The two signals in a single record were properly detected and processed respectively.

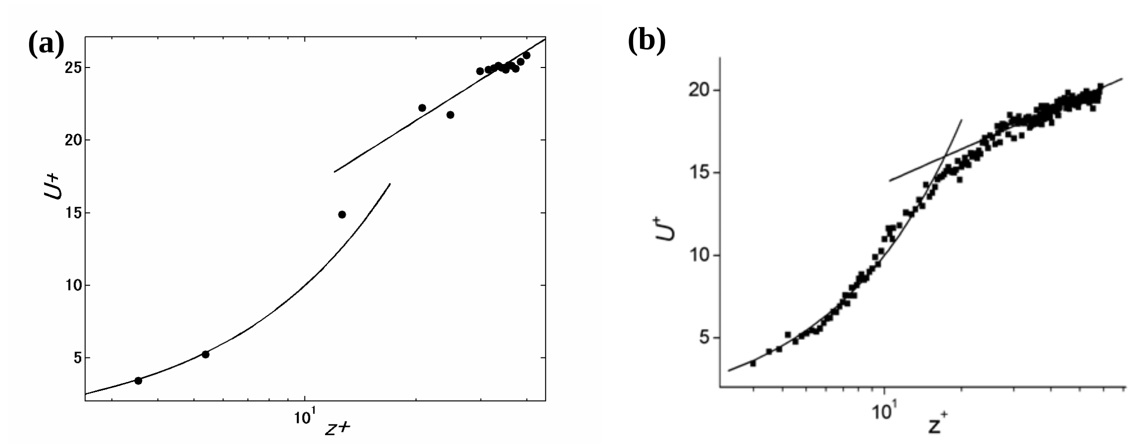

Fig. 7 Comparison of signal processing techniques: (a) use of the former technique, (b) use of new technique; Data used for this comparison is the same measurement data taken in a turbulent boundary layer.

4. Summary

A signal processing technique was developed for the measurements in turbulent boundary layers with velocity-profile sensor. The technique enabled the processing of data with a wide range of velocity, which occurs in the measurements in turbulent boundary layers. It is based on the adaptive time-window and dynamic filtering techniques described in the present paper. The signal processing was realized in an offline method, which processes the recorded signal afterward measurements. In the signal evaluation several validation conditions were included in order to reduce outliers. The developed processing technique was applied to the real measurement signals taken in a turbulent boundary layer. A comparison was done for processing with a former processing technique and with the newly developed one. It was demonstrated that the new technique effectively detects signals of various velocities measured in the turbulent boundary layers. One of the further challenges is to extend this technique to an online processing with a higher data rate.

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