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EVALUATION OF THE APPROXIMATE LINEAR DYNAMIC RESPONSE OF A CONSTANT TEMPERATURE ANEMOMETER

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Abstract. *The purpose of the present paper is to carry out an experimental characterisation of the dynamical response of a low cost hot-wire anemometer. To evaluate the circuit dynamics, a square wave has been imposed to the reference offset voltage of the anemometer. The frequency response of the constant-temperature bridge has been obtained through a sine-wave test. The experimental bandwidth of the circuit operation in a real flow measurement condition was characterized through a sine-wave test in the range of 1Hz to 1MHz. Results have been compared with the theoretical transfer functions of second and third order. This comparison has shown that, depending on the particular conditions of each test, a second or third order model should be used. The natural frequency of the circuit and the damping ratio have also been found.*

keywords: *How-wire anemometer, Frequency response, Dynamic response, Turbulence, Experimental methods.*

1. Introduction

Hot-wire anemometry (HWA) is certainly the most traditional and important experimental technique when it comes to the establishment of the characteristics of a given turbulent flow field. Despite the many recent advances in alternative techniques that have led the field of experimental methods in fluid mechanics to an apparent level of much higher complexity, the HWA remains a very useful technique with the additional advantage of being very simple, easy-to-use, and low-cost. Furthermore, HWA is renowned for its reliability and robustness.

The popularity of the HWA has made this technique extremely well established. As such, some practices have become almost standard, routine procedure. One important concept that is frequently overlooked by researchers is the dynamic response of a constant temperature anemometer (CTA). This is, however, a crucial knowledge that is intimately related to a correct signal analysis on the frequency domain.

Turbulent flows are intrinsically very complex in nature. Even though the motion of fluids are governed by deterministic equations, the Navier-Stokes equations, turbulent motions are characterised by randomness in space and time, by the richness of scales of eddy motion and by a high degree of diffusivity. As a result, turbulent flows are typically treated on a statistical basis. Theories advanced to solve these problems are based on the concept of the Reynolds average, which decomposes an instantaneous flow field into time-averaged and fluctuating components. An statistical analysis of fluctuating components then gives us an outline of the behaviour of the turbulent flow field.

The above remarks imply that a characterization of the real dynamics of a turbulent flow field can only be possible if an instrument with high frequency response is available. More importantly, the signal response must be correctly generated, acquired and treated, so that its theoretical statistical treatment can be deemed valid, thus providing a good estimate for the phenomenon under study. In particular, the analysis on the frequency domain of the CTA output signal can furnish valuable results on time and length scales of the flow, and especially on the energy distribution along the characteristic wavenumbers of the flow. The spectral analysis of the response signal can give us important information on how turbulent eddies are produced, how energy is transferred from large eddies down to small eddies, and in which way energy is dissipated by the smallest scales of the flow.

The main objective of this brief account is to point out to the reader the extreme importance in obtaining reliable and representative data on experimental measurements in turbulent flows. In particular, we will specifically discuss data obtained through hot-wire anemometry. The present paper will explain how user-defined parameters can influence the frequency response of a CTA bridge, and will discuss the role of these parameters on the dynamic behaviour of the circuit. Typical tests presented in the literature to evaluate the transient response of the circuit in real measurement conditions will be described in detail. The results will be compared to approximated theoretical models.

To achieve our objective, the present paper will describe the dynamic response of a low cost hot-wire anemometer that is being developed at the Laboratory of Turbulence Mechanics of PEM/COPPE/UFRJ. Considerable improvements have been made on the main typical anemometer system, especially by introducing the use of digital controllers. These modifications are noticed to contribute to the increase in the signal to noise ratio. To evaluate the circuit dynamics, both a square wave and a triangular wave have been imposed to the reference offset voltage of the anemometer. The frequency response of the constant-temperature bridge has been obtained through a sine-wave test. The experimental bandwidth of the circuit operation in a real flow measurement condition was characterized through a sine-wave test in the range of 1Hz to 1MHz. Results have been compared to the theoretical transfer functions of second and third order. This comparison has shown that, depending on the particular conditions of each test, a second or third order model should be used. The natural frequency of the circuit and the damping ratio have also been obtained.

This manuscript is organized as follows. In section two we present the basic principles of operation of the hot-wire anemometer, together with a brief literature review. The description of the experimental apparatus is made in section three. The results are introduced in section four. The main conclusions of the present work are summarized in the last section.

2. A brief literature review

Hot-wire anemometry (HWA) is based on the convective heat transfer process that takes place when a heated wire is exposed to a fluid flow (Lomas (1986), Brun (1995), Perry (1982), Jorgensen (2002)). Because typical sensors are less than 5 μm in diameter and are made to withstand high temperatures, any change in fluid flow condition that affects the transfer of heat from the wire to the medium will be sensed immediately by a constant temperature HWA system. HWA can then be used to measure the velocity and temperature of the flow.

In general, one of the most important aspects of thermal anemometry is the accurate interpretation of the anemometer signal. The main purpose of any sensor calibration is to determine, as accurately as possible, the relationship between the anemometer output voltage and the physical property under consideration, in this case velocity or temperature.

Among the several possible methods that can be devised to characterise the velocity and temperature dependence of thermal anemometers signals, King's law is the most traditional one, Eq. 1. Through this procedure, the heat transfer from the probe is assumed to be proportional to a product of the temperature difference $T_w - T_a$ and a function of the velocity, where T_w is the temperature of the heated wire and T_a is the ambient temperature. The output voltage, E_0, of a constant temperature hot-wire anemometer can hence be represented by:

$$E_0^2 = A + B\bar{U}^n (T_w - T_a), \tag{1}$$

where A, B and n are constants to be determined, and $\bar{U}$ is the mean flow. More details of the basic principles of operation of the constant temperature anemometer can be found in Loureiro et. al. (2002).

The simplified circuit of a typical CTA bridge is presented in Fig. 1, where R_W is the wire hot resistance, R_a and R_c set the bridge ratio, L_b compensates the inductance of the cable, R_b compensates the resistance of the cable and sets the final temperature, K is an equivalent gain of the amplifier, E_S is an off-set voltage needed to allow the circuit to begin to operate and is responsible for its stability. In order to set the wire overheat, one must define a value for R_b. Then, the wire resistance/temperature is only determined by R_a/R_c since the Wheatstone bridge is automatically balanced by the feedback amplifier (Weiss (2002)).

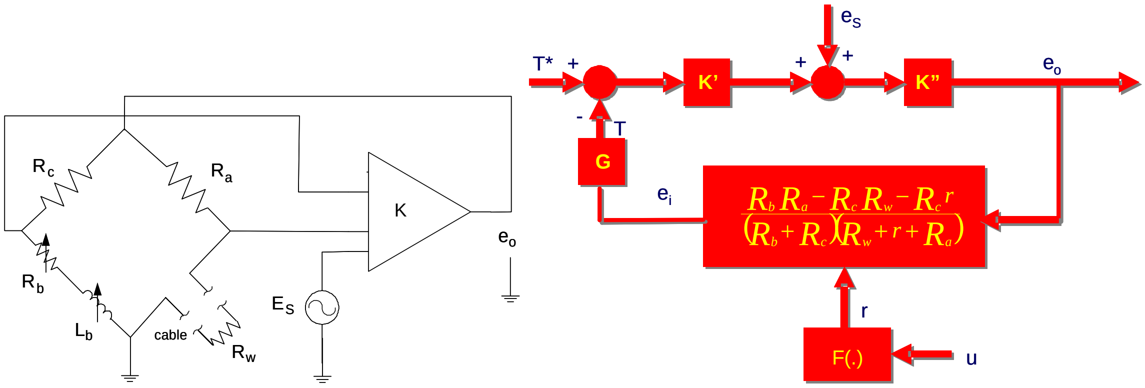

Figure 1: Simplified circuit of the CTA bridge (on the left) and block diagram of the feedback system (on the right).

For the dynamic tuning of the CTA, the direct method consists in superimposing sinusoidal velocity variations of known amplitude to a constant flow field. All methods available, however, are of difficult accomplishment and are restricted to low frequencies.

The linear control approach of hot-wires to constant temperature has been reported in the literature by different authors, e.g. Perry (1982), Freymuth (1997), Weiss (2002). The earliest theory was the first order approximation introduced by Weske (1943). Basically, this theory represented the role of the amplifier gain in overcoming the thermal lag caused by the hot-wire thermal inertia, what allowed for achieving high frequency response. The importance of proper damping for optimization of the frequency response was discussed by Kovasznay (1948) in the context of a linear theory.

This linear theory was extended to a third order theory by Berger et al. (1963) and also by Freymuth (1977), so that the effects of second order damping on frequency optimization could be accounted for.

However, Perry and Morrison (1971) and Wood (1975) supported the view that a second order control theory was sufficient to describe the dynamics of modern constant temperature hot-wire anemometers. The authors admit that the system has basically three poles, and one of these poles has a magnitude far beyond the range of interest in anemometers' applications. Therefore, a second order theory is a faithful description of the problem. More recently, though, Freymuth (1997) supported that a third order theory is essential.

The present work has then decided to evaluate both the second and the third order theory against eight different test cases. The procedure generally used to evaluate the CTA dynamics is to impose an electrical perturbation on the circuit. Lomas (1986) suggests the application of the perturbation signal in parallel to the hot-wire on the Wheatstone bridge, whereas Perry (1982) proposes that the perturbation should be added to the reference offset E_S voltage of the circuit. This latter method was used in the present work.

If the perturbation signal is e_s, and e_0 is the output voltage then a perturbation analysis yields:

$$e_0 = \frac{K_2(T_1 s + 1)e_s + K_1 u}{T^2 s^2 + 2\zeta T s + 1}, \tag{2}$$

where u is a perturbation velocity. The small voltage signal disturbance e_s and the velocity perturbation u are decoupled in the numerator of Eq. 2. Therefore, by analysing the CTA response due to e_s in the frequency domain, we can obtain the bandwidth for the velocity fluctuations. The constants of Eq. 2 are functions of the bridge parameters.

The simplified block diagram of the feedback system is presented in Fig. 1, where r is a variation on R_w due to the influence of the flow on the heat transfer process and F(.) is a non-linear function. For small perturbations the system can be modeled by transfer functions relating e_o to e_s and to u, which coefficients are functions of the circuit parameters and the operation point. Fig. 2 shows how the systems' poles and zeros are generally affected by E_S, K, $\bar{U}$ and the overheating factor a.

3. Experimental apparatus

The Laboratory of Turbulence Mechanics has two open-circuit wind tunnels. The larger tunnel was specially designed and constructed to simulate environmental flows. A detailed description of this facility can be found in Cataldi et. al. (2001). The second one is a low-turbulence wind tunnel with turbulence intensity levels of the order of 0.2%. This facility can be set to run at velocities that can reach 10 m/s. Its test section is 4 m long and the cross section area is 0.30 x 0.30 m.

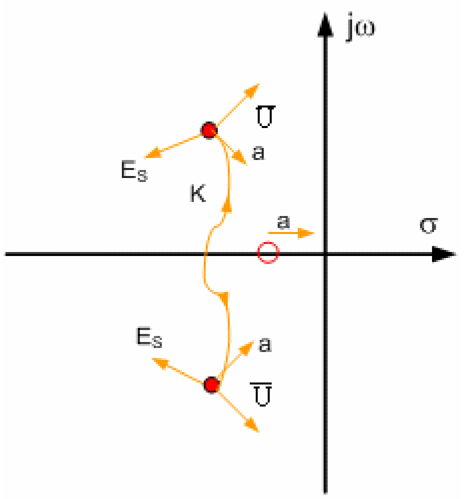

Figure 2: Poles displacement as functions of E_S, K, $\bar{U}$.

Both tunnels have honeycombs and screens to control the turbulence levels and to guarantee a uniform flow. The computer-controlled traverse gears are two-dimensional and capable of positioning sensors with an accuracy of 0.1 mm. For the present work, both wind tunnels were used. The experiments were conducted in a controlled environment, with the laboratory temperature set to 18.0 $^oC \pm 0.5\ ^oC$. An illustration of the atmospheric wind tunnel is shown in Fig. 3. The frequency response tests were performed on the low speed wind tunnel. In addition, measurements on the flow in the wake of a circular cylinder were conducted at the aerodynamic wind tunnel.

Figure 3: Illustration of the low speed wind tunnel.

The main wind tunnel characteristics are:

- Circuit: open.
- Test section: 0.67 m high, 0.67 m wide and 10 m long.
- Wind speed: continuously variable from 0 to 3.5 m/s.
- Longitudinal pressure gradient: adjustable to zero by means of an adjustable ceiling.

- Turbulence intensity: below 2
- Number of resistances used to heat the incoming air: 10.
- Resistances capacity: 10 kW.

A hot-wire probe, made at the Laboratory of Turbulence Mechanics-UFRJ, is illustrated in Fig. 4, which also shows the sensor in position inside a wind tunnel.

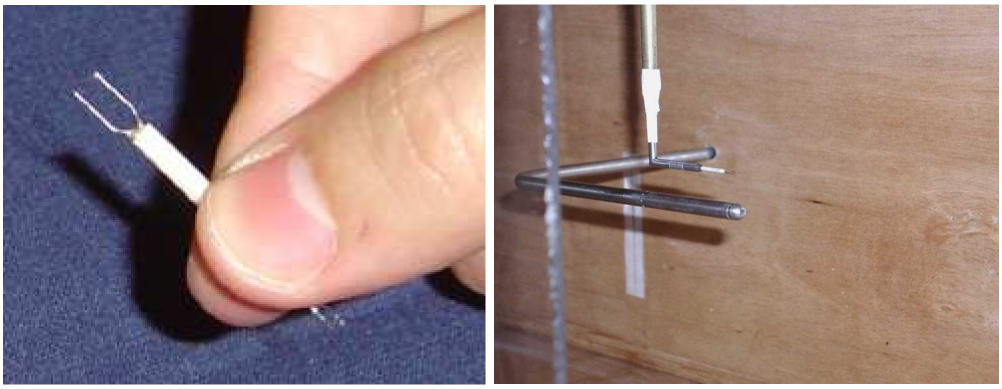

Figure 4: Illustration of a single hot-wire sensor (on the left) and a Pitot tube along with a hot-wire sensor inside the wind tunnel (on the right).

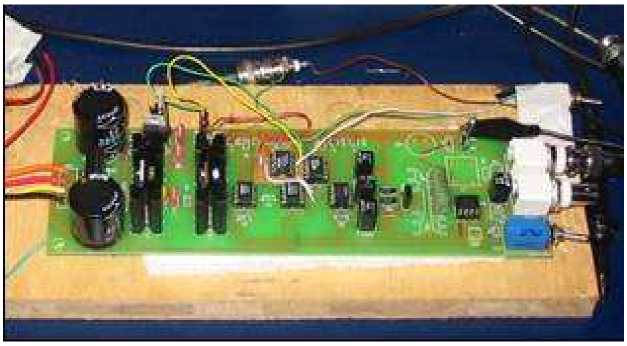

Figure 5: Illustration of a prototype of the constant temperature anemometer bridge.

4. Results

The constant temperature anemometer was developed and constructed in the Laboratory of Turbulence Mechanics (PEM/COPPE/UFRJ). Some improvements have been added to the original design in order to let this instrument to be controlled digitally, and for the entrance parameters to be adjusted by computer. The resistances used for the adjustment of the overheating ratio were substituted by digital potentiometers, and their values are set by a computer interface actuating on a dedicated micro-controller. A separate circuit used to perform the dynamical response test has also been included to the anemometer. An illustration of the prototype of the hot-wire anemometer is presented in Fig. 5.

The tests were performed with a Dantec hot-wire probe model 55P15, in a 20:1 Wheatstone bridge rate. The sensor was placed inside the wind tunnel, exposed to the freestream. Eight different operating conditions listed in Table 1 were specified by modifying E_S, K, $\bar{U}$ and a. For the present experiments, the only parameter that was not varied was the bridge inductance L_b.

4.1. Frequency response tests

The frequency response test was performed by adding a sine-wave perturbation to the reference offset voltage, in the range of 1 Hz to 1 MHz. This test was applied to each case listed in Table 1. All the results are shown in Fig. 6.

Table 1: Configuration of the performed tests.

Case	$\bar{U}(m/s)$	OHR	Gain K	Offset $E_S(V)$)
1	1.5	1.8	200	0.583
2	3.0	1.8	200	0.583
3	1.5	1.5	200	0.583
4	1.5	1.8	100	0.583
5	1.5	1.8	200	2.500
6	1.5	1.8	200	0.517
7	1.5	1.5	200	0.517
8	1.5	1.8	100	0.517

Please note the detrimental effects of using a low overheat ratio (Case 3) and a high offset voltage values (Case 5). These results are characterised by the absence of a well defined peak frequency and smaller bandwidths. The optimum operational condition is shown in Case 8, which presents a sharp peak and the highest frequency bandwidth. It must be highlighted here that the final frequency response to the fluid flow is flat until the peak frequency. For higher frequencies, the response is attenuated by 40 dB/decade.

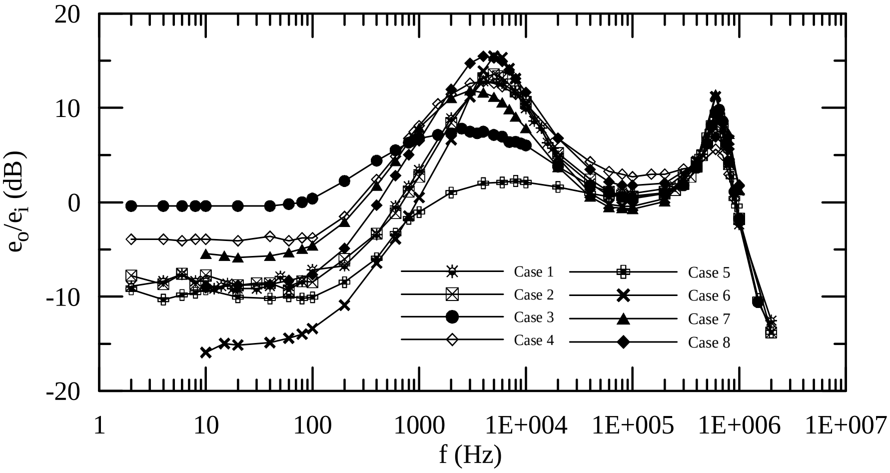

Figure 6: Frequency response test.

4.2. Square-wave test response

The results of the transient and frequency response tests were used to identify the transfer functions for each case. First, we assume that the CTA can be modeled by a transfer function with two complex poles, a real zero and a gain, as suggested in Perry (1982). Hence, the high frequency dynamics shown in Fig. 6 must be neglected, and the first resonant peak and its peak frequency must be calculated. The parameters of the theoretical transfer functions are obtained by performing a comparison between the simulated and the measured step responses. If the second order simplification does not agree with the real square-wave response, then a third real pole and a second real zero are added to the transfer function. The estimated functions are shown in Table 2. Fig. 7 shows the agreement between the experimental and simulated step responses for the eight cases studied.

As can be seen, in three of the eight tested cases the system had to be modeled with a third order transfer function, Fig. 7c, 7d and 7e, which corresponds to Cases 3, 4 and 5. Although the added pair of real zero-pole has magnitude considerably larger than the dominant poles and zero, its effect must be considered in order to have a near perfect agreement between the simulated and the experimental step responses. These results support the conclusions of Freymuth (1997).

Table 2: Results for the transfer functions adjusted to the experimental square-wave response.

Case	Poles	Zeros	Gain
1	-26200 ± j 21300	-1000	220000
2	-25000 ± j 24000	-700	221000
3	-6000 ± j 1500	-1200	200000
	-100000	-9000	
4	-14000 ± j 100	-800	260000
	-45000	-13000	
5	-8500 ± j 3000	-600	170000
	-160000	-10000	
6	-20800 ± j 31300	-350	221000
7	-23300 ± j 6100	-1500	187000
8	-25000 ± j 18000	-800	291000

4.3. Experimental Measurements

To verify the anemometer response and the analysis performed above, measurements have been carried out in a turbulent wake behind a circular cylinder. The results are illustrated in Figure 8. With the hot-wire placed approximately at the shear layer which is formed behind a circular cylinder, measurements were performed for two different potential flow velocities U, Fig. 8a and Fig. 8b. The signal responses were analysed in the frequency domain to determine the frequency in which vortices were shedding. The calculated Strouhal number are in the range of $S = 0.18$, where $S = nD/U$, n is the vortice shedding frequency and D is the diameter of the cylinder ($D = 23$ mm). For the present Reynolds number, $R_e \approx 10^4$, these results are in good agreement with the predictions of classical theory (see Schlichting (1979)). The characteristic behaviour of the inertial sublayer is illustrated in Fig. 8d.

5. Conclusion

The present work has described tests performed to illustrate the dynamics of a low cost hot-wire anemometer developed at PEM/COPPE/UFRJ. The transfer functions for the CTA have been derived for eight different operating conditions, from experimental data obtained with the injection of sine and square-wave perturbations on the circuit. The bandwidth of the circuit was characterized through a frequency response test using a sine-wave in the range of 1Hz to 1MHz. The transient response of the system has been assessed by the imposition of square-waves on the reference offset voltage of the circuit, together with the hot-wire sensor exposition to a real flow field. The work has shown that for some conditions the second order modeling is not acceptable, only a third order transfer function allows a near perfect fitting between the simulated and experimental results.

Measurements in the flow behind a circular cylinder have been carried out in order to illustrate the performance of the CTA anemometer. Results present a good agreement with theoretical predictions.

Plans for the future include a comparison of the present results with the response of a commercial CTA bridge and the development of thermal anemometry to perform measurements is separated flows.

6. Acknowledgements

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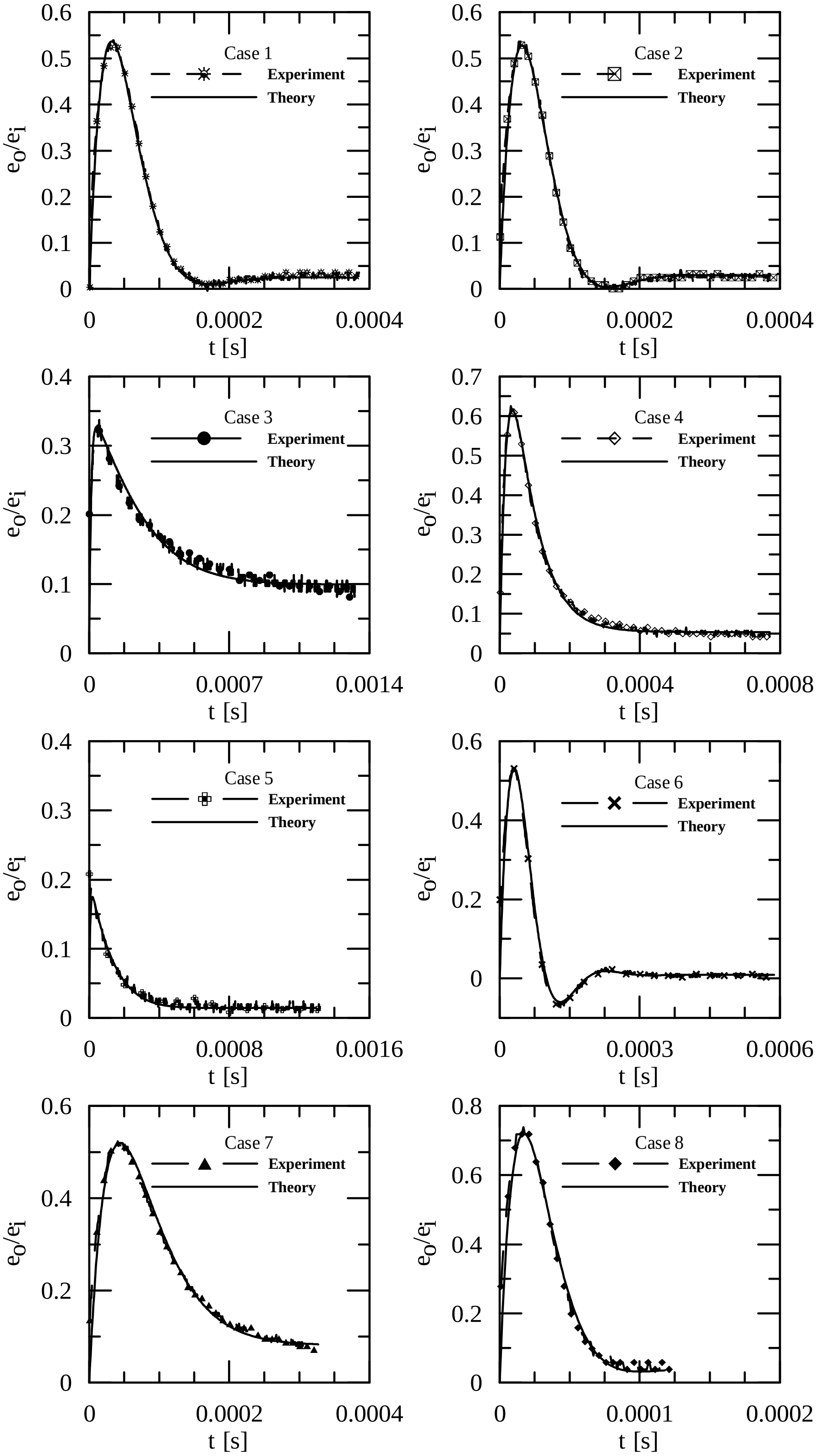

Figure 7: Square-wave test.

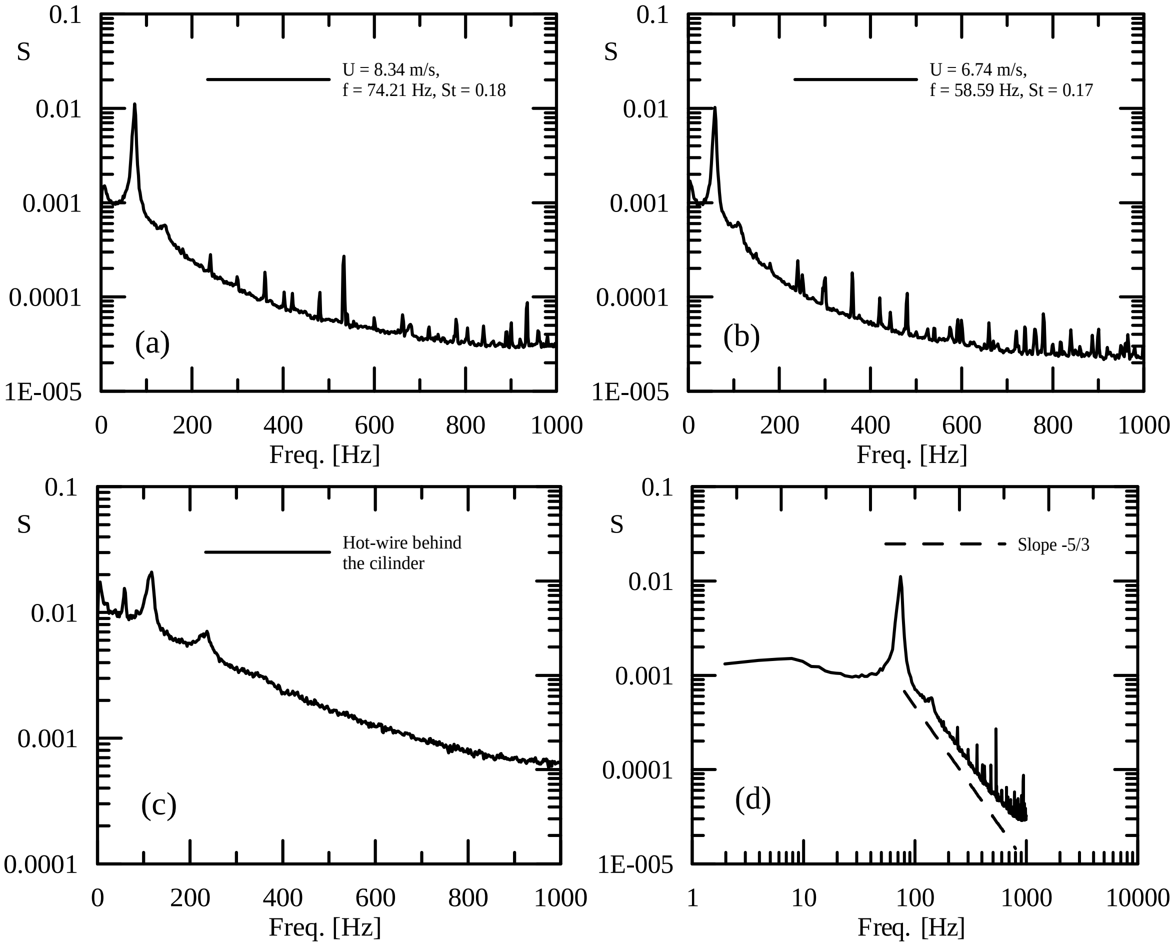

Figure 8: Flow behind a circular cylinder. Spectral analysis of the measurements performed with the CTA bridge at: (a) the mixing layer, $U_\infty = 8.3$ m/s, (b) the mixing layer, $U_\infty = 6.7$ m/s, (c) the wake flow, (d) illustration of the characteristic behaviour of an inertial sublayer.