Pitot tube designed for high frequency inflow measurements on MW wind turbine blades

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Pitot tube designed for high frequency inflow measurements on MW wind turbine blades

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Abstract:

This paper is dedicated to the development of a measurement device which can be used to capture turbulence characteristics of the inflow onto a MW wind turbine blade. The measurement device is designed as Pitot tube which measures total and static pressure fluctuations with microphones. The usable frequency response of the Pitot tube is at least 5 kHz. The tubing leading to the microphones causes resonance frequencies due to Helmholtz resonance. The signal of the static pressure had to be corrected with a transfer function found in an experiment. The Pitot tube was tested in a wind tunnel and the measured turbulence spectra were compared with the measurements of a hot wire anemometer placed in the vicinity. The agreement was very good in a frequency range of 500 – 3000 Hz.

Keywords: wind shear, turbulence, inflow, five hole pitot tube.

1 Introduction

Even though a considerable number of field experiments on wind turbines were conducted, turbulent fluctuations data of the inflow to the blade up to high frequencies are lacking. However, the spectral composition of the inflow has a strong influence on the blade performance. It can influence the position of the point of transition for example. The inflow phenomena which trigger transition are expected to be in the frequency range between 1 and 3 kHz. Therefore there is a need of information about the high frequency fluctuations of the inflow for advanced rotor and blade design of MW wind turbines. In most previous experiments five hole Pitot tubes were used to measure the inflow characteristics, because they are very robust. On the other hand, the usable frequency response of those Pitot tubes is very limited. Sonic anemometers which are often used on meteorological masts offer a higher usable frequency response, but they cannot be mounted on a rotating rotor. Hot wire anemometers are successfully used in wind tunnel tests. The usable frequency response reaches up to 10 kHz for fiber film probes which are the most robust hot wire probes. But the diameter of fiber film probes measures only 70µm. That makes them inappropriate for outdoor experiments.

In the past years Risø National Laboratory made good experience with condenser microphones for the detection of transition on airfoils. The microphones proved to be robust and yield an excellent signal to noise ratio. The range of the usable frequency response is comparable to hot wire anemometers. This paper is dedicated to the development of a Pitot tube, which uses microphones instead of classical pressure transducer for the conversion of the fluid dynamic pressure into an electric signal.

2 Method

2.1 Probe design and usage

The measurement device is designed as a Pitot tube to measure static and total pressure fluctuations. It shall be used on 2.3MW wind turbine blade in the vicinity of a conventional five hole Pitot tube with low usable frequency response in the Tjæreborg experiment, Figure 1.

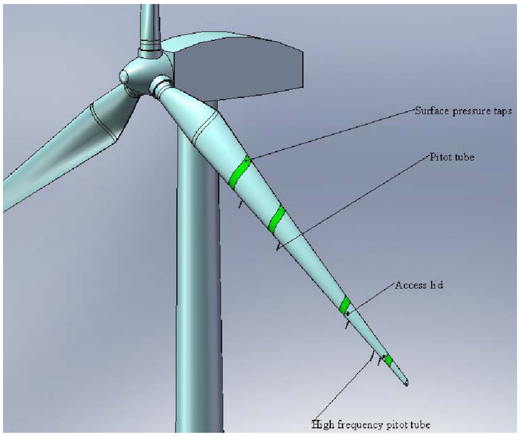

Figure 1: Blade of a 2.3MW wind turbine equipped with measurement devices

The Pitot tube will be placed on the blade for a period of several days to collect information about the inflow in the frequency domain from 500 to 5000Hz.

2.2 Requirements and design goals

The usable frequency response of the Pitot tube has to be high. For wind turbine applications inflow fluctuations of at least 3 kHz have to be measured, but a usable frequency response of 5 kHz is desirable. The probe diameter has to be small compared to the wave length of the smallest resolvable fluctuations[1].

It has to be robust against all weather conditions so that it can be used in measurement campaigns of one week or more.

The Pitot tube is designed to measure only total and static pressure in order to keep the probe diameter small. Sennheiser back-electret condenser microphones of type KE 4-211-2 were used to convert pressure fluctuations into an electric signal. Their diameter of 4.75mm made a five hole Pitot tube design while keeping the probe diameter reasonable small impossible.

The microphones shall be placed as close to the surface of the Pitot tube as possible. The most dominant flow disturbances are caused by Helmholtz resonance in the tubing and volume in front of the microphones. The Eigen-frequencies of those disturbances have to be higher than the frequency range of interest.

The boundary layer flow has to be kept laminar at the position of the static pressure holes. A turbulent boundary layer would introduce spurious noise to the measurement signal of about the same order as the free flow fluctuations. Calculations with XFOIL were made during the design process of the geometry in 2D to find the best configuration for keeping the flow laminar.

The pressure hole diameter has to be as small as possible. Big pressure holes would disturb the flow too much. Experience shows that the pressure hole diameter should be between 0.3 and 0.5 mm.

2.3 The Helmholtz resonator

Helmholtz resonance plays an important role in the design of the tubing leading to the pressure sensors and the volume in front of them. The Eigen-frequencies induced by Helmholtz resonance are much lower than Eigen-frequencies due to standing waves in the tubing. They can influence the frequency range of interest. The Helmholtz resonator is the acoustic equivalent to a linear mass-spring-damper system in mechanics. A model of the Helmholtz resonator is depicted in figure 2.

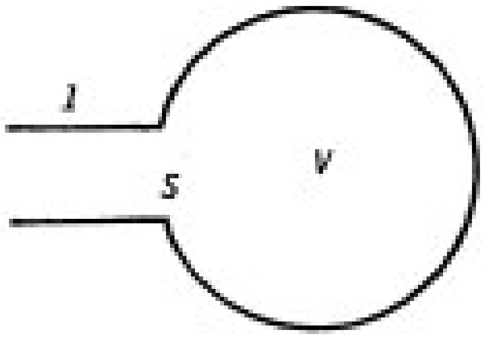

Figure 2: Model for a Helmholtz resonator from [5]

The air in the bottle neck with length l and cross sectional area S is compressible and acts like the spring and damper in the equivalent mechanical system. The air in the body with Volume V is assumed to be incompressible. It is the equivalent to the mass in the mechanical system.

The Eigen-frequency of the Helmholtz resonator is given by [5] as

$$\omega_0 = c\sqrt{\frac{S}{Vl_{eff}}} \qquad (1)$$

The assumption of no damping is made in equation (1). Instead of the true length of the of the bottle neck l the effective length l_{eff} has to be applied, because of the inertia of the air in the bottle neck. To calculate the effective length, the relation

$$l_{eff} = l + 2 \cdot 0.8\sqrt{S/\pi} \qquad (2)$$

given by [6] was used.
From equation (1) on can conclude that if the Eigen-frequency of the Helmholtz resonator should be high, the cross sectional area S has to be big, the length l of the bottle neck has to be short and the body volume V has to be small. However, the requirement of a large cross sectional area is in conflict with a small pressure hole diameter. Thus, the Eigen-frequency of the resonator has to be kept high by making the tubing very short. The body volume can be kept small to a certain extend, but it is strongly dependent on the measures of the microphone itself. However, equation (1) gives only an estimate of the real Eigen-frequency of the system. It was therefore only used in the design process of the Pitot tube. The Eigen-frequency was determined experimentally.
The transfer function between excitation force and answer of the equivalent mechanical system in frequency space is given in reference [3]. It reads

$$H(\omega) = \frac{1}{1-(\omega/\omega_0)^2 + i2\varsigma\omega/\omega_0} \qquad (3)$$

The measured signal can be corrected for Helmholtz resonance if the Eigen-frequency of the undamped system ω0 and the damping coefficient is known. They will be determined experimentally.

2.4 Conversion of pressure fluctuations into velocity fluctuations

Microphones measure only pressure fluctuations, but not the mean value of the pressure. It will be shown that the pressure fluctuations can be directly interpreted as velocity fluctuations, if the mean velocity is known.
The following assumptions are made:

- no friction (inviscid)
- flow along streamline
- incompressible flow
- hydrostatic pressure gradient can be neglected

In a first approach we also assume steady flow. The Bernoulli equation can be written as

$$\overline{V} + \tilde{V}(t) = \sqrt{\frac{2}{\rho}(\overline{p}_{dyn} + \tilde{p}_{dyn}(t))} = \overline{V}\sqrt{1+\frac{2}{\rho\overline{V}^2}\tilde{p}_{dyn}(t)}$$

(4)

if the velocity and the pressure are represented as the sum of mean value and fluctuation component. A Taylor expansion of the expression under the square root and ignoring second and higher order terms yields a simple relation between pressure and velocity fluctuations

$$\tilde{V}(t) = \frac{1}{\rho\overline{V}}\tilde{p}_{dyn}(t). \qquad (5)$$

This is an important result, because it is not necessary to know the mean value of the dynamic pressure. The mean value of the velocity can be taken from measurements with a conventional five hole Pitot tube placed in the vicinity.
The assumption of steady flow might be pretty poor for high frequency fluctuations. Ref.[2] found an exact solution for the unsteady Bernoulli equation describing the flow around a translating sphere. It reads

$$p_{dyn} = \frac{\rho}{2}\left[\frac{V^2}{4}(9\cos^2\varphi - 5) - R\frac{dV}{dt}\cos\varphi\right]. \qquad (6)$$

At the stagnation point (φ=0º) the pressure distribution around the ellipsoid which is the shape of the tip of the Pitot tube is similar to the one of a sphere. Therefore it will be assumed that equation (6) is valid for the Pitot tube only in the stagnation point. Equation (6) at φ=0º with the decomposition of pressure and velocity into mean value and fluctuation component reads

$$2\overline{V}\tilde{V} + \tilde{V}^2 + R\frac{d\tilde{V}}{dt} = \frac{2\tilde{p}_{dyn}}{\rho}. \qquad (7)$$

This nonlinear differential equation can be solved numerically, if the mean value of the velocity and the time series of the dynamic pressure fluctuations are known.
In the experiments described in this paper the pressure was converted into velocity by equation (5) which assumes steady flow. A numerical method to solve equation (7) is not known to the author yet, but it is assumed that such a method exists and will be found soon.

2.5 Experimental validation

The Pitot tube was tested in two different experimental setups. The first experiment (Experiment 1) was conducted to detect the Eigen-frequencies caused by Helmholtz resonance. The Pitot tube was placed together with a reference microphone of the same type as used in the Pitot tube. A speaker was placed in a variable distance to the Pitot tube and the reference microphone, figure 3.

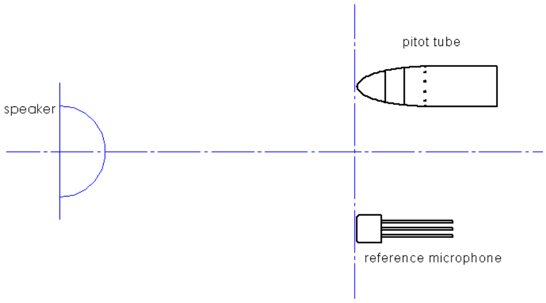

Figure 3: Experimental setup for detection of resonance frequencies (Experiment 1)

The distance between speaker and Pitot tube is the same as the distance between speaker and reference microphone. The distance between reference microphone and Pitot tube was 60mm. The distance to the speaker was varied between 100mm, 150mm and 200mm. The speaker emitted a sweep signal starting at 1 Hz and ending at 10 kHz with duration of 2s. However, the directional pattern of the speaker could cause a different physical signal at the position of the Pitot tube compared to the physical signal at the position at the reference microphone. No investigation about the directional pattern was undertaken, so this remains as uncertainty in the experimental setup. Another uncertainty is caused by the fact that the experiment was not conducted in a silent room.
The second experiment (Experiment 2) was conducted in the wind tunnel of Denmark's Technical University, DTU. The setup is shown in figure 4.
The test section of the wind tunnel has a quadratic cross sectional area of 500mm times 500mm length. 500mm upstream of the measurement instruments a grid was mounted to introduce turbulence into the flow. Three different grid geometries were used. They created turbulence of different characteristic length scales and turbulence intensities.

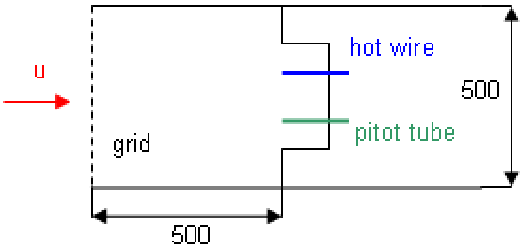

Figure 4: Experimental setup for wind tunnel tests

The Dantec MiniCTA hot wire anemometer system with a triaxial sensor was used to measure the turbulence and the measured velocity spectrum was compared to the one measured by the Pitot tube. The distance in the direction normal to the flow between the Pitot tube and the hot wire anemometer was 150mm.
The turbulence intensity in the wind tunnel is about 0.1% if no grid is in the flow.

3 Results

3.1 Pitot tube geometry

The diameter of the pitot tube is 14mm. The shape is formed elliptically and the tube length is 150mm, figure 4.

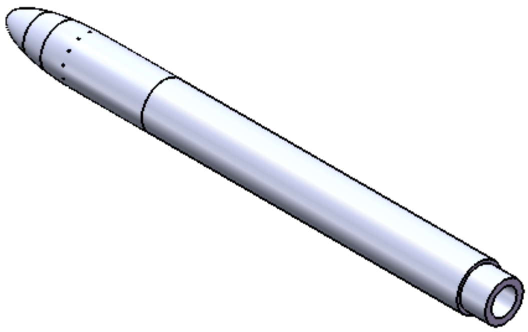

Figure 5: Isometric view of the pitot tube

The total pressure hole has a diameter of 1mm. With this large diameter the Eigen-frequency due to Helmholtz resonance calculated with equation (1) is at about 11 kHz. And as the flow velocity in the vicinity of the stagnation point is small, disturbances introduced by the large pressure hole won't be strong.
For static pressure measurements 12 pressure holes were evenly distributed over the probe diameter at a distance of 1.7 probe diameters downstream of the tip. The diameter of the static pressure holes was 0.5mm. Even though these

geometric setup doesn't correspond to the Helmholtz resonator model (because the bottle has 12 instead of 1 neck), the Eigen-frequency was estimated by equation (1) during the design process. It is at 3.9 kHz.

3.2 Transition point calculations with XFOIL

To estimate the point of transition, calculations with XFOIL were performed. The Pitot tube geometry was approximated as a spanwise infinitely extended flat plate with the two dimensional contour of the Pitot tube. The length was set to 110mm, because at that stage of the design process the length of the Pitot tube was not known and it has very little influence on the point of transition. The calculation were performed for Mach number M=0.2 which corresponds to a flow velocity U=70m/s. The Reynolds number based on the length of the Pitot tube is $Re_L=5.53*10^5$. The Reynolds number based on the probe diameter is $Re_D=6.4*10^4$. The exponent n of the e^n-criteria was set to 9. For angles of attack α up to 5º the location of transition on the suction side (S_tr) and on the pressure side (P_tr) are given in table 1.

α [º]	S_tr [mm]	P_tr [mm]
0	41,294	41,283
1	35,794	110
2	33,099	110
3	30,382	110
4	27,324	110
5	23,067	110

Table 1: Location of transition calculated with XFOIL

Transition on the pressure side has only to be considered in the case of 0º angle of attack. However, according to the calculations it is located 17mm further downstream than the position of the static pressure holes (which are located at 24mm). The transition point on the suction side is located downstream of the static pressure holes for angles of attack up 4º. However, due to the high n factor used in the calculations and the assumed two-dimensionality the results have to be interpreted carefully and the true transition point might be located further upstream.

3.3 Experimental detection of resonance frequencies

The placement of the Pitot tube in Experiment 1 was adjusted that either the total pressure hole or the static pressure holes had the same distance to the speaker than the reference microphone. First the total pressure hole was at the same distance to the reference microphone and the total pressure signal was measured. The magnitude of the transfer function between the reference microphone signal and the total pressure microphone signal is shown in Figure 6.

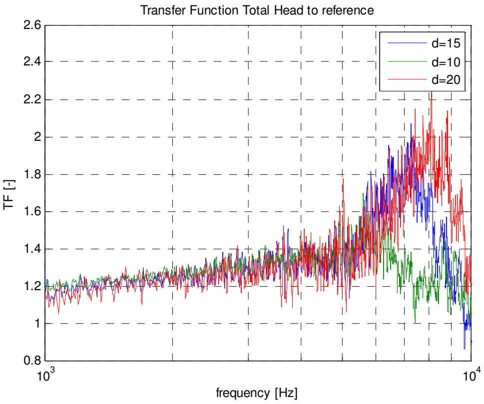

Figure 6: Transfer function between reference microphone signal and total pressure microphone signal

An amplification of the total pressure signal over the frequency range between 1 to 10 kHz can be seen. There is a very strong amplification in the frequency range of 5 to 10 kHz. But this amplification varies with the distance between speaker and total pressure hole. It might be caused by the interaction of the standing wave between speaker and Pitot tube and the tubing leading to the total pressure microphone. Because of the ambiguity of the measured transfer function the total pressure signal can not be correct for the detected amplification. The experiment has to be repeated in a silent room with a stronger speaker at a larger distance to the total pressure hole.

To detect the resonance frequency of the static pressure tubing system the Pitot tube was shifted in a way that the static pressure holes were the same distance away from the speaker as the reference microphone. The magnitude of the transfer function between the reference microphone signal and the static pressure microphone signal is shown in Figure 7.

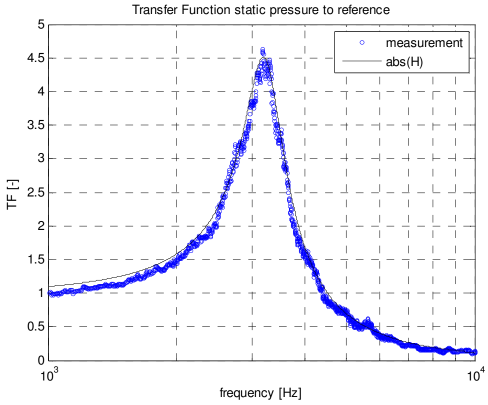

Figure 7: Transfer function between reference microphone signal and static pressure microphone signal

The transfer function between the signal of the reference microphone and the signal of the static pressure microphone was independent of the distance to the speaker. It is strongly influenced by Helmholtz resonance. The magnitude of the transfer function given by equation (3) fits very well to the result of the measurement if the natural Eigen-frequency of the undamped system is set to f0 = 3240 Hz and the damping constant is set to ζ = 0.1116. It is plotted as black line in Figure 7.
To correct the measured static pressure, the signal was transferred into Fourier space. The result was multiplied with the inverse of the transfer function given by equation (3) and transferred back into time domain. The magnitude of the transfer function between the reference microphone and the corrected static pressure signal is shown in Figure 8.

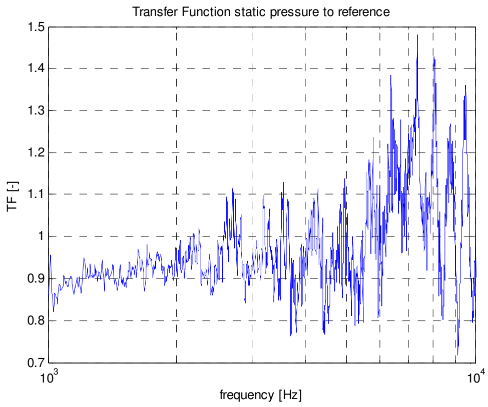

Figure 8: Transfer function between reference microphone signal and corrected static pressure signal

3.4 Wind tunnel experiments

For the investigation of the influence of the correction of the static pressure, measurements without a turbulence grid were made. In Figure 9 the power spectral density of static and total pressure is shown for an estimated wind speed of 55m/s.

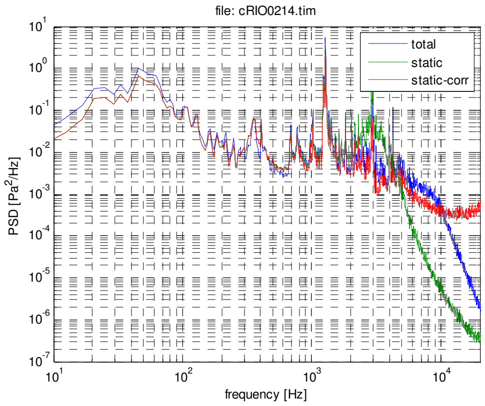

Figure 9: PSD of pressure signals for u=55m/s and no grid

The signal of the uncorrected static pressure shows a significant peak at about 3000Hz. When the correction method is applied, the peak disappears and the static pressure corresponds well with the total pressure in a frequency range up to 10 kHz. As the turbulence intensity in the wind tunnel without a turbulence grid is low, the agreement between static and total pressure is expected and proves that the correction method works well. On the other hand, the correction function amplifies strongly the signal in the domain above 10 kHz. This restricts the usable frequency response of the Pitot tube to 10 kHz.
Figure 10 shows the comparison of the velocity spectrum measured with Pitot tube and hot wire anemometer at estimated wind speed 45m/s and a grid with the wire thickness of 5mm and the distance of the wires of 25mm inserted in the wind tunnel.
The measured spectra agree well in the frequency range between 500 and 3000 Hz. However the spectrum measured with the Pitot tube shows some very narrow peaks in this frequency range. As those peaks can not be found in the spectrum measured with the hot wire anemometer, it must be caused by the interation of the Pitot tube with the flow. Are more accurate calibration method as performed in experiment 1 might solve this problem.
In the frequency range above 3000 Hz the spectrum measured with the Pitot tube has a higher amplitude. This corresponds well to the

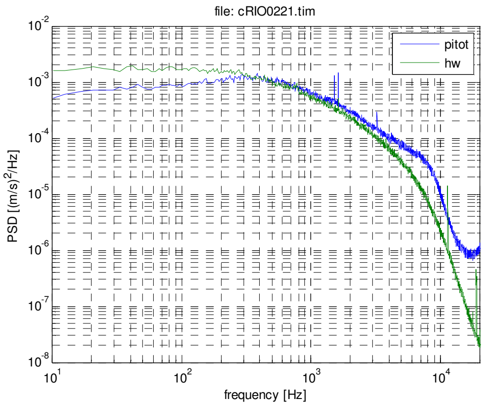

Figure 10: Velocity power spectral density at u=45m/s and grid 5

observation from experiment 1 that the signal measured by the total pressure microphone was amplified. This problem can also be solved by calibration with a similar setup as in experiment 1, but in a silent room.
Figure 11 shows the comparison of the velocity spectrum measured with Pitot tube and hot wire anemometer at estimated wind speed 45m/s and a grid with the wire thickness of 6mm and the distance of the wires of 30mm inserted in the wind tunnel.

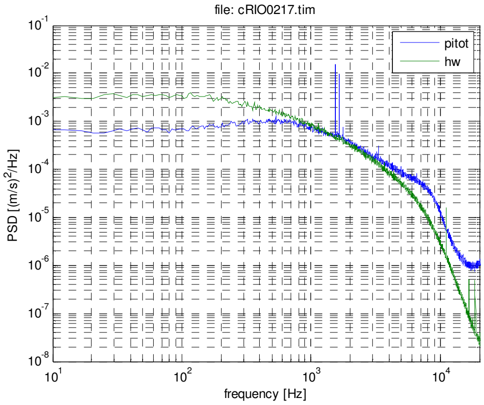

Figure 11: Velocity power spectral density at u=45m/s and grid 6

The agreement up to a frequency range to 3000 Hz is well again for this case. However, the spectra deviate strongly in the low frequency range. The tubes of the turbulence grid are thicker than in the case before. Therefore the Reynolds number based on the tube diameter is higher as well and the turbulence structures are expected to be finer. That means more energy is shifted to higher frequencies. This tendency is more significantly observed in the spectrum of the Pitot tube.
The narrow peaks in the spectrum measured with the Pitot tube in the frequency range are even stronger in this case than in the previous. During the measurement the grid caused a strong tonal noise which might cause resonance in the Pitot tube geometry which could explain this peak. It can be solved by calibrating the Pitot tube at a higher sound pressure level than in experiment 1 to find a transfer function to correct for those resonances.

4 Conclusions

A Pitot tube using microphones for signal conversion was developed. It proved to be a robust measurement tool which is suitable for the use on MW wind turbines. The measured pressure fluctuations can be converted into velocity fluctuations if the mean value of the velocity is known. The mean value of the velocity can be measured by a traditional 5-hole Pitot tube placed in the vicinity.
However, the calibration method of the Pitot tube has to be improved. The transfer function between the reference and the pressure signals has to be measured in a silent room that it can be directly applied on the measured signal. An amplification of the total pressure signal was detected, but due to the ambiguity of the measured transfer function no correction could be applied. The transfer function for the static pressure showed a similar behaviour as a Helmholtz resonator model. Parameters of the theoretical transfer function of this system could be adjusted to fit the measurements and the signal could be corrected.
The comparison of velocity spectra measured with the Pitot tube and a hot wire anemometer showed a strong deviation in the frequency range above 3000 Hz. This could be caused by the amplification of the total pressure signal or due to the fact that the probe is not small compared to the wavelength of fluctuations above 5000 Hz. A smaller probe should be developed.
Furthermore the spectra of the velocity fluctuations measured with the Pitot tube showed narrow peaks in the frequency range between 1000 and 3000 Hz. The phenomena triggering transition are assumed to be in this frequency range. Therefore those peaks have to be avoided by a better calibration method.

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