Design and Construction of a Test Stand for Noise Measurements on Model Propellers

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Introduction

Unducted propellers are a highly efficient means to provide propulsive force. Their main disadvantage, however, is their high noise generation. For this reason there is considerably interest in understanding the noise generation of propellers and the development of potential noise reduction techniques.

One approach to investigate propeller noise is to perform measurements in a wind tunnel. In the present paper, the process of designing and constructing a test stand for acoustic and aerodynamic measurements on model propellers in the small aeroacoustic wind tunnel at BTU Cottbus is shown. Thereby, special attention is paid to the definition of crucial parameters that allow for the transfer of the model-scale results to existing propellers.

Theory

Measurements on propellers in a model scale are very cost efficient and a complementary method to both experiments on real propellers and numerical investigations. Furthermore, they allow for the investigation of a large number of different variations. Of course it is desired that the results are then transferred back from the model to the original propeller, and therefore the model has to capture the physical processes and conditions that are found at the real propeller. Since the propeller noise emission is closely related to the aerodynamic parameters, a noise analysis is only meaningful when the aerodynamic parameters are known at the same time.

It is therefore necessary to define those parameters that sufficiently describe the basic aerodynamics and acoustics of a propeller. Basically, an unducted propeller can best be imagined as a circular disc that "moves through the air" having a flow speed U. It generates a pressure difference and hence accelerates the air moving through the propeller, effectively adding the velocity ΔU to the air flow (see Figure 1). The resulting parameters that describe, in a simplified way, the propeller aerodynamics and acoustics are

- parameters characterizing the properties of the fluid, like the flow speed U, the speed of sound c_0, the fluid density ρ_0 and the dynamic viscosity μ,
- parameters characterizing the propeller, like the **propeller diameter $\boldsymbol{d}$**, the **number of blades $\boldsymbol{B}$** and the **rotational speed $\boldsymbol{\omega}$**,
- the aerodynamic parameters, like the thrust T, the torque Q and the velocity ΔU added to the flow or
- acoustic parameters, like the (rms) sound pressure $\tilde{p}$, the frequency f and the observer distance r (e.g. the distance of a microphone at a fixed angle).

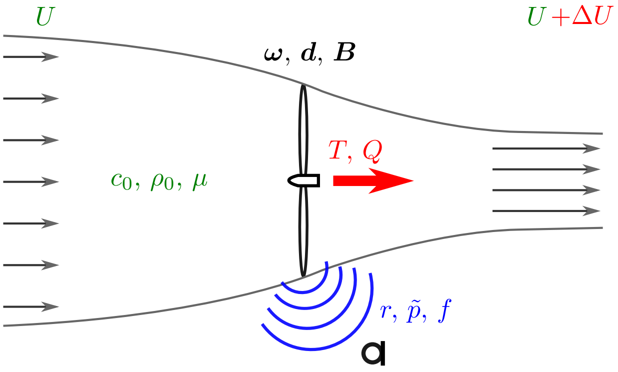

Figure 1: Parameters that describe basic propeller aerodynamics and acoustics

Some of these parameters cannot be varied when performing measurements in a wind tunnel facility. For the aeroacoustic wind tunnel to be used for the measurements these are mainly the fluid parameters c_0, ρ_0 and μ. Other parameters, like the flow speed, the propeller diameter, the number of blades, the rotational speed and the microphone distance are variable quantities. The remaining parameters (thrust, torque, added velocity, sound pressure and frequency) are resulting quantities that are a direct consequence of the measurements.

The next step now is to define a set of dimensionless quantities to describe both the noise generation and the basic aerodynamics of a propeller based on the 13 dimensionful (or non-dimensionless) parameters shown in Figure 1. To this end, a dimensional analysis [2] was performed on these parameters, yielding that a set of only 10 dimensionless parameters is needed to fully describe the system.

In general, when performing measurements on objects in a model scale the ideal solution would be to keep all dimensionless quantities of the original system (here: the real aircraft propeller) constant, which would allow to transfer all findings without any limitations from the model to the real object. This, unfortunately, is not possible in reality. Therefore, it is important to define those crucial dimensionless quantities that necessarily have to be kept constant in order to allow for the transfer of the most significant results from the model to the real object.

In the present case, the dimensionless parameters that should be the same for original propeller and model are

1. the number of blades B,
2. the advance ratio

$$J = \frac{U}{\omega \cdot d}, \tag{1}$$

   which describes the propeller pitch as the advance of the propeller in flight direction per revolution and hence is a main parameter to characterize the aerodynamic performance of a propeller,

3. the Mach number

$$Ma = \frac{U}{c_0}, \tag{2}$$

4. the Strouhal number

$$Sr = \frac{f}{B \cdot \omega}, \tag{3}$$

5. the (aerodynamic) efficiency

$$\eta = \frac{T \cdot U}{\omega \cdot Q}, \tag{4}$$

   as the ratio of the propulsive power (or thrust performance) that accelerates the aircraft to the driving power (or shaft power),

6. a term that could best be described as the normalized pressure

$$\frac{T}{(\rho_0 \cdot c_0^2 \cdot d^2)}, \tag{5}$$

   since it normalizes the pressure that acts on the propeller disc due to the thrust T with the air pressure $p_0 = \rho_0 \cdot c_0^2$, and

7. the ratio of the velocity, that is added to the fluid flow by the propeller, to the flow speed,

$$a = \frac{\Delta U}{U}. \tag{6}$$

Another dimensionless quantity, that can be derived as a function of the advance ratio J and the Mach number Ma, is the helical Mach number

$$Ma_h = \frac{\sqrt{U^2 + (\omega \cdot d/2)^2}}{c_0}. \tag{7}$$

It describes the ratio of the total velocity acting on the propeller blade (due to the forward motion and the rotational motion) to the speed of sound and is an important measure when characterizing propeller noise.

Besides the dimensionless quantities that should be the same for both original propeller and model propeller, there are other dimensionless quantities that cannot be kept the same in the present aeroacoustic wind tunnel:

8. the Reynolds number based on propeller diameter,

$$Re = \frac{U \cdot \rho_0 \cdot d}{\mu}, \tag{8}$$

   which cannot be kept constant since the fluid properties would then have to compensate for the smaller diameter (thus requiring a considerably lower viscosity),

Parameters

U [m s^{-1}]
ΔU [m s^{-1}]
T [kg m s^{-2}]
Q [kg m^2 s^{-2}]
B [-]
ω [s^{-1}]
d [m]
c_0 [m s^{-1}]
ρ_0 [kg m^{-3}]
μ [kg m^{-1} s^{-1}]
p [kg m^{-1} s^{-2}]
f [s^{-1}]
r [m]

Dimensionless Quantities

blade number B
advance ratio $J = \frac{U}{\omega \cdot d}$
Mach number $Ma = \frac{U}{c_0}$
Strouhal number $Sr = \frac{f}{B \cdot \omega}$
(aerodynamic) efficiency $\eta = \frac{T \cdot U}{\omega \cdot Q}$
normalized pressure $\frac{T}{(\rho_0 \cdot c_0^2 \cdot d^2)}$
velocity ratio $a = \frac{\Delta U}{U}$
Reynolds number $Re = \frac{U \cdot \rho_0 \cdot d}{\mu}$
acoustic efficiency $\eta_{ac} = \frac{\tilde{p}^2 \cdot r^2}{\rho_0 \cdot c_0 \cdot \omega \cdot Q}$
normalized distance r/d

Figure 2: Overview of dimensionful (left column) and dimensionless (right column) parameters that are the basis of the present propeller test stand design (the bold parameters should necessarily be the same for the original propeller and for the model)

9. the (acoustic) efficiency

$$\eta_{ac} = \frac{\tilde{p}^2 \cdot r^2}{\rho_0 \cdot c_0 \cdot \omega \cdot Q}, \tag{9}$$

   which is the ratio of the acoustic power, derived from the far-field sound pressure, the microphone distance and the characteristic acoustic impedance, to the driving power and

10. the distance of the microphone normalized by the propeller diameter,

$$\frac{r}{d}. \tag{10}$$

An overview of the 13 dimensionful parameters and the resulting dimensionless quantities is given in Figure 2.

Test Stand Design

Concept

A test stand for measurements on model propellers basically consists of a force sensor to measure the aerodynamic forces, a motor to drive the propeller and the model propeller to be examined. In this section, the requirements for the different parts of the test stand will be defined. This calculation is performed based on two considerations: First, the dimensions of the wind tunnel test section are of general importance, since they have an influence on the maximum size of the test objects. Second, the estimation is based on the data of an original propeller and the aforementioned requirement to keep crucial dimensionless parameters from the original

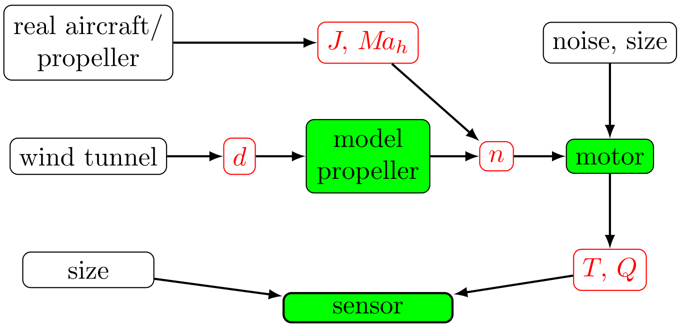

Figure 3: General steps of the basic design process

propellers the same for the model propeller. In the present case, the data were obtained from a small aircraft type *Cessna 150*, which has a two-bladed fixed propeller made by Mc Cauley [3].

The basic steps of the design process are shown in Figure 3.

Propeller

In a first step, the dimensions of model propellers to be examined in the existing wind tunnel facility are defined. The desired propeller test stand will be included in the aeroacoustic open jet wind tunnel at BTU Cottbus, a facility characterized by a very low background noise and, in absence of any turbulence generators, by a very low turbulence [4]. From several nozzles of different geometry that are available it was decided to use a circular nozzle with a diameter of 0.2 m for the propeller test stand. After recent modifications of the wind tunnel, the maximum flow speed that can be achieved with this nozzle is approximately 90 m/s.

The maximum diameter for propeller models basically depends on the size of the wind tunnel nozzle only. The circular area of the propeller disc should not exceed 60 % of the nozzle area [5], resulting in a maximum propeller diameter of 0.12 m when using the chosen nozzle. Since a common diameter for model aircraft propellers is 4.75” (0.12 m), all calculations and subsequent measurements were performed for model propellers of this size.

Motor

To obtain a rough estimate for the required specifications of the motor, a simple comparative calculation was performed based on the data from the Cessna 150. The original propeller has a diameter of 1.7 m. For a typical flight speed of 54 m/s and a rotational speed of the propeller of 2750 rpm the resulting advance ratio according to equation (1) is 0.69. Based on the International Standard Atmosphere model, at an altitude of 4000 m the air temperature is approximately 262 K, leading to a speed of sound of 324 m/s. The resulting helical Mach number according to equation (7) is 0.77.

In the next step, the rotational speed of a model propeller with a diameter of 0.12 m, that results in the same advance ratio and the same helical Mach number, has to be estimated. Using both equation (1) and (7), the rotational speed of the model propeller operating in the aeroacoustic wind tunnel can be obtained. For a speed of sound of 343 m/s this results in a relatively high rotational speed of approximately 687 s^{-1} (or 41,215 rpm) that the model propeller has to endure and that the motor has to provide.

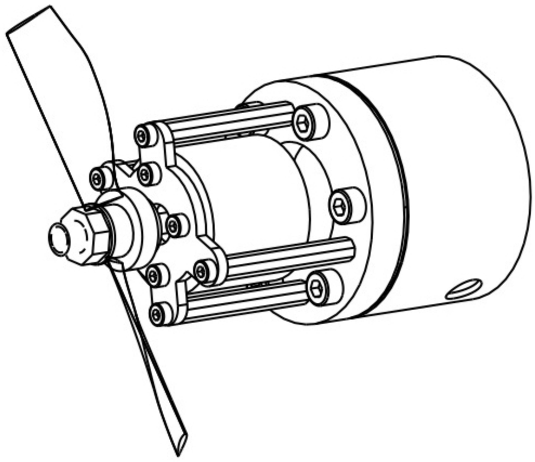

Figure 4: Schematic of the model propeller, the DC motor and the multi-axis sensor

Additionally, an estimative stress analysis was performed based on propeller blade element theory [1] to validate that the model propeller withstands the mechanical stresses, which have their maximum at the base of the propeller blade, at these rotational speeds. Furthermore, it is important that the propeller is balanced in order to avoid high dynamic loads that may lead to the destruction of the model.

Besides the high rotational speed that is necessary, the motor has to meet several additional demands: It has to be sufficiently small to not disturb the air flow behind the propeller, and, since the test stand is designed for acoustic measurements of propeller noise, the motor should be as quiet as possible. It was finally decided to use a brushless DC electric motor in “inrunner” configuration (where the can of the motor contains the rotational core), since inrunner-type motors spin considerably faster than outrunner-type motors. The selected motor is small, with a diameter of 36 mm and a height of 30 mm. It provides a maximum power of 710 W and a continuous power of 560 W. The idle speed is 5,300 rpm/V, and hence the desired speed of 41,215 rpm can easily be realized.

Initially it was desired to perform experiments on contra-rotating propellers, too. Such propellers are driven by contra-rotating motors via coaxial contra-rotating shafts. However, additional effort is necessary to find a small electric motor that is capable to provide the required high rotational speeds. Therefore, at the present time the research focuses on common propellers only.

Force Sensor

Now that the motor is chosen, the maximum forces and moments acting on the model propeller can be estimated. This is done based on the classical airscrew momentum theory [1] by Rankine and Froude for inviscid flow. For a given mechanical power the maximum thrust is generated during start, when $U = 0$. For a maximum motor power

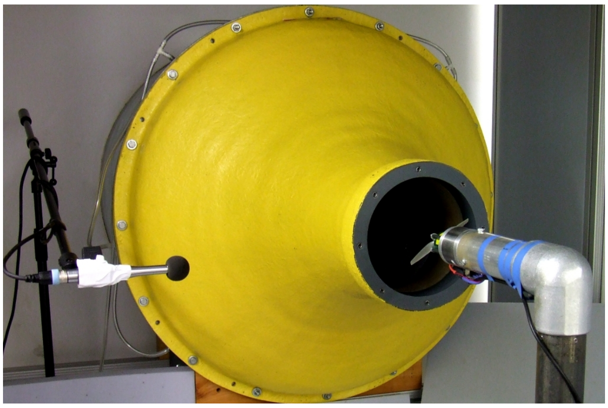

Figure 5: Photograph of the test setup in the aeroacoustic wind tunnel at BTU Cottbus

of 710 W the resulting thrust of a propeller of 0.12 m diameter is approximately 23.9 N. When assuming a low rotational speed of only 1000 rpm for the start of the propeller ($\omega = 0$ is mathematically not possible) a torque of 6.8 Nm can be calculated.

Another force that was included in the estimation process is the impulse force that acts on the propeller and on the motor due to the flow. For a maximum flow speed of 90 m/s, the selected motor with a diameter of 0.06 m, a model propeller of 0.12 m diameter with eight blades and a blade root diameter of 0.02 m near the hub, an impulse force of approximately 75 N can be estimated. The influence of other forces and moments acting on the model propeller was also considered.

Finally, a multi-axis sensor suitable for the measurement of three forces and three torques was chosen. It has a diameter of only 0.06 m. The maximum forces are 200 N in the directions perpendicular to the flow and 500 N for the in-flow direction, the according maximum torques are 5 Nm and 10 Nm, respectively.

Resulting Test Stand

The propeller, the motor and the sensor were connected to a frame made of a steel pipe with an outer diameter of 0.6 m. The horizontal arm of the stand has a length of 0.33 m, and hence an undisturbed flow behind the propeller is accounted for. The resulting initial version of the propeller test stand, consisting of the model propeller, the DC motor and the multi-axis sensor, is shown in Figure 4.

Initial Measurements

First measurements were performed on a model propeller, during which the test section of the wind tunnel was surrounded by a cabin with absorbing sidewalls that provide a nearly anechoic environment for frequencies above 500 Hz. The propeller used for the measurements was a two-bladed 4.7” × 4.0” propeller, which means it has a diameter of 0.12 m and a pitch of 0.10 m. The signals from the multi-axis force sensor were recorded using 24-bit full-bridge input modules, the rotational speed was determined from the motor driving signal using a 16-bit analog input module. All acoustic measurements were performed with a 1/2” measurement microphone, positioned at a horizontal distance of 0.42 m from the propeller axis in its rotational plane. Figure 5 shows a photograph of the test setup.

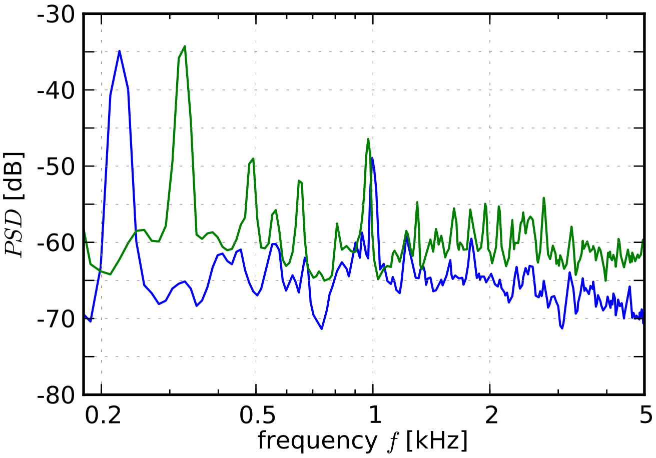

Figure 6: Results of initial acoustic measurements on a two-bladed 4.7” × 4.0” model propeller for different rotational speeds, power spectral density *re* $4{\cdot}10^{-10}$ $\mathrm{Pa}^2/\mathrm{Hz}$ (— 108 rps, — 160 rps)

Acoustic results measured at the propeller for two rotational speeds are presented in Figure 6. The power spectral density features the spectral peaks that correspond to the blade passage frequency $f = B \cdot \omega$ and their harmonics.

Conclusion

A test stand for aerodynamic and acoustic measurements on model scale propellers in an open-jet wind tunnel was successfully designed based on a dimensional analysis. Using data from a real aircraft propeller, the requirements regarding the model propellers to be examined, regarding the motor and regarding the force sensor were defined. Finally, initial acoustic measurements were performed on a two-bladed model propeller using a single microphone. The corresponding results were presented.

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