EXPERIMENTAL SETUP FOR MEASUREMENT OF CONTRA-ROTATING PROPELLERS

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Abstract
A multi-thrust and multi-torque aerodynamic balance has been designed for measuring thrusts and torques of a pair of coaxial contra-rotating propellers. The setup allows the independent measurement of performance of each propeller. The results of measurement of first pair of propellers in static thrust mode are presented and indicate the methodology that will be used for future measurements. Various aspects, such as propeller distance and speed of rotation ratio are investigated.

Keywords: contra-rotating propellers, coaxial drive, aerodynamic balance, static thrust.

1 Introduction
Contra-rotating coaxial propellers are claimed to be more efficient than conventional single propeller units. The relatively little use of the contra-rotating propellers in the real world applications could be contributed to their inherent mechanical complexity, but could it be also due to the fact, that their performance often falls short of the bold manufacturer’s claims? The user guide for a contra-rotating propeller drive system states: “Contra-Rotating Propeller systems are 15% to 20% more energy efficient than equivalent single propeller systems. This is because the air passing through the blades of the propellers is accelerated twice in order to generate thrust, instead of a single time as it is with single propeller systems.”[1] The whole problem is much more complex from the fluid dynamics point of view than these simplified and often misleading claims suggest.

There is one main aspect of the propellers in contra rotating motion which should provide superiority over conventional single propellers. The downstream propeller reduces or almost eliminates the rotational motion of the fluid thus reducing the losses due to additional momentum in the wake and diminishing the reaction torque. There are also other benefits linked to this design, such as highest maximum thrust obtained without experiencing high Mach tip speed losses or removal of gyroscopic effect.

Numerical model using boundary element method and incorporating integral boundary layer model [2] is being developed at the Department of Fluid Dynamics and Thermodynamics, CTU in Prague, in parallel to the experimental study. For proper validation, solid experimental data for verification of the model are required. The measured quantities are the thrust, torque and rpm of each propeller. Since a complex test facility has to be build, some other experiments are also planned in the future in order to obtain some data outside of the numerical model validation scope of work. These include acoustic measurements and wake visualization.

2 Practical Considerations
For powering the setup, the only suitable option are electric motors, combustion engines were ruled out at the beginning. Three basic configurations were considered (see Fig. 1):

2. Motors mounted to a common mount attached to walls via streamlined structures. Pros: Separated thrusts and torques. Cons: Minimal propeller distance is too large, structure influences flow between propellers, limited space for balance components.


![Figure 1: Possible configurations of contra-rotating coaxial propeller drive](image)

From the three configurations, the least viable is the second option, which can be ruled out. The first and third option both carry some implementation difficulties. From aerodynamic point of view, first configuration is better, while the third one has the benefit of using standard motors and simple balance design. Since the results are meant to be used for numerical model verification, where empty space at the inlet is considered, the first configuration was chosen, despite the inevitable difficulties connected with coaxial drives.

The first parameter of the test stand which needed to be decided was the overall size of the setup. The size is limited by the price and availability of coaxial motors and propellers. At the same time, higher Reynolds numbers are desirable, in order to minimize the viscous effects on the solution and to be able to use the stand in the future for testing of contra rotating propellers of large drones. A pair of 22-inch contra-rotating propellers was designed at the department and used for testing. An advantage of such in-house designed solution is the availability of the exact CAD geometry that was used for the manufacture. A 6kW coaxial electric motor drive type DOUBLE AXI 5330/20 was chosen as the drive unit, which can take various propeller sizes, depending on the pitch, with up to 24 inches of diameter.

3 Description of the test stand

3.1 Mechanical design

The mechanical design is shown in Fig. 2. The Zemic L6D load cells of various load capacities were chosen as force sensing elements. The coaxial motors were delivered with stators bolted together. The stators have been disconnected and joined together by a mount with radial ball bearing \( \text{ CONFIG 1 } \), which allows the stators to rotate freely with respect to each other. The upwind motor \( \text{ CONFIG 2 } \), which powers the downwind propeller is firmly connected to a three-armed support structure formed by three pairs of 3kg load cells measuring thrust \( \text{ CONFIG 3 } \) and torque \( \text{ CONFIG 4 } \) acting on the motor mount. The
stator of the downwind motor is axially fixed to the upwind rotor. The spinning of the stator is prevented by an arm 6 extending to a 6kg load cell 7, which measures the torque indirectly.

The upwind propeller is firmly connected to the inner shaft 8, so its thrust is measured by the motormount load cells. Its torque is measured by the already mentioned 6 kg load cell. The downwind propeller transfers its torque via 4 pins 9 into the upwind motor (the torque is measured by the motormount), but it is not fixed axially to the motor. The thrust force from the upwind motor is transferred via three pull rods 10 to a dedicated 20kg load cell 11. The electric motors are controlled by two separate speed controllers and powered by a common lead-acid 24V 110Ah battery. The aerodynamic balance (see Fig. 3) is mounted to a stiff aluminum column, part of a rigid frame (Fig. 4), which acts as a support and also holds a protection mesh.

Figure 2: The coaxial motor power unit including force measuring motor mount
3.2 Measured quantities

The signals from the bridges of the 8 load cells are converted to digital signal by an in-house designed A/D converter. Each load cell has been calibrated separately, before being mounted in the aerodynamic balance. A pair of thrust forces $T_1, T_2$ [N] and a pair of torques $M_1, M_2$ [Nm] are calculated based on the values provided by load cells and calibration data. Zero force reading is performed before each run. An infra-red photodiode is installed near the casing of each outrunner motor for the measurement of rotational speed. Room temperature, atmospheric pressure and relative humidity are noted before each measurement to obtain the density of air. The speed of rotation of each propeller can be adjusted manually at the moment using mechanical dials. PC-to-Controller interface is being manufactured, so in the future the whole process of measurement will be automated.

4 Measurement results

4.1 Performance parameters

The initial measurements are performed outside of the wind tunnel with no capability of providing non-zero freestream velocity. This means that the propellers are currently investigated under static conditions $v_\infty = 0$ where the advance ratio $\lambda = 0$. The performance parameters are usually non-dimensionalised to allow better comparison across different propellers and different flow regimes. For single propeller, the coefficient of thrust $c_t$, power coefficient $c_p$, and efficiency $\eta$ (equations 1,2,3) are defined based on its diameter $D$, measured forces, shaft power $P = M\omega$ [W] and rotational rate $n$ [1/sec].
\[ c_t = \frac{T}{\rho m^2 D^4} \]  
\[ c_p = \frac{P}{\rho m^2 D^5} \]  
\[ \eta = \frac{c_t \lambda \pi}{c_p} = \frac{T v_\infty}{P} \]  

Note, that in literature, the thrust and power coefficients can be expressed differently, so care must be taken before comparing results from different authors.

Since the standard propeller efficiency is a measure of how efficiently is the device propelling an object forward, it always reaches zero in static conditions. Different definition of efficiency, the “static thrust efficiency” or Figure of Merit (FoM), tells us how much power would an ideal propulsor of the same diameter require for a given thrust in relation to the real propeller power input.

Investigation of the performance of the propellers strongly depend on the correct definition of the Figure of Merit, which is not unique and its definition for contra rotating propellers is not as straightforward as it might seem [3]. The definition of Figure of Merit is based on the ideal propulsor theory and observing the change of momentum and kinetic energy of the fluid flowing through the propeller disc. If the exit flow velocity in sufficient distance behind the propeller is \( v_e \) the Figure of Merit becomes [4]:

\[ \text{FoM} = \frac{\dot{m} \left(0.5v^2_e - 0.5v^2_\infty\right)}{P} \]  

From ideal propulsor theory it follows [5] that the flow velocity at the propeller plane is equal to the average of \( v_e \) and \( v_\infty \). The thrust force \( T \) from the change of momentum is:

\[ T = \dot{m} (v_e - v_\infty) \]  

And the mass flow can be expressed at the propeller plane of area \( A \) as:

\[ \dot{m} = \rho A \frac{(v_e + v_\infty)}{2} \]  

By choosing \( v_\infty \to 0 \) the following equations are derived for the power of ideal propulsor and FoM:

\[ \dot{m} = \rho A \frac{v_e}{2} \]  

\[ T = \dot{m} v_e = \rho A \frac{v^2_e}{2} \]  

\[ P_{id,\,\text{prop}} = 0.5 \dot{m} v^2_e = \rho A \frac{v^3_e}{4} = \frac{T^{3/2}}{\sqrt{2\rho A}} \]  

\[ \text{FoM} = \frac{P_{id,\,\text{prop}}}{P} = \frac{T^{3/2}}{P \sqrt{2\rho A}} \]  

The above relations are relevant to any propulsion system (not considering duct), since the mechanism of producing thrust is not important in the equations. The ideal propulsor is a disk with a discontinuity pressure jump across its surface and virtually any propulsion device can be compared against it to produce a Figure of Merit. There are several issues that can be taken into account in a more complex definition of the FoM [3], but as long as a reasonable disc area \( A \) is used for the calculation, the presented solution is valid. The pair of propeller discs in a contra-rotating propellers can have different diameters \( D_1 \neq D_2 \). By using for example the average of the two diameters, an FoM higher than one is possible. For this reason, the larger area of the two propeller discs should be used in the calculation \( A = \max(A_1, A_2) \).
The following definitions (11,12,13) are used for evaluating the performance of a contra-rotating system of propellers.

\[
c_t = \frac{T_1 + T_2}{\rho(0.5n_1^2 + 0.5n_2^2)(0.5D_1^4 + 0.5D_2^4)} \tag{11}
\]

\[
c_p = \frac{P_1 + P_2}{\rho(0.5n_1^3 + 0.5n_2^3)(0.5D_1^5 + 0.5D_2^5)} \tag{12}
\]

\[
FoM = \frac{(T_1 + T_2)^{3/2}}{(P_1 + P_2)\sqrt{2\rho A}} \tag{13}
\]

### 4.2 Measurement procedure

To verify the test rig’s ability to provide reliable performance data, a pair of 22” carbon fiber propellers (Fig. 5), designed at the department, was manufactured by a cooperating company and was mounted on the setup. The upwind propeller has a pitch of 18” and was designated PT22x18E5-CR-R01, the second (downwind) propeller has a pitch of 20” and designation PT22x20E5-CR-R01. The influence of the propeller distance and rotational speed ratio was tested. The propeller distance-to-diameter ratio was first set to \( R_{DD} = 0.07 \), where the gap between trailing edge of first propeller and leading edge of second propeller was only 2 mm near the root. Then the distance was increased by 40mm to \( R_{DD} = 0.14 \). The rotational rate ratio defined in this work as \( R_{RR} = n_1/(n_1 + n_2) \) was tested in the range between 0.3 and 0.7.

![Mounted propellers for the initial measurements](image)

**Figure 5: Mounted propellers for the initial measurements**

### 4.3 Influence of Reynolds number for the case of matched rpms

In the first test, the rotational rate of both propellers was kept the same (in opposite direction of course), and the rpms were gradually increased to the maximum revolutions possible. The aim of this experiment was to verify if the increase in static thrust efficiency (FoM) due to higher Reynolds number could be distinguished and how the high relative error for low thrusts and torques impacts the measurement.
Figure 6: Figure of Merit vs. Reynolds number, with error bar showing standard deviation

The Fig. 6 shows that the Figure of Merit remains almost constant throughout the Reynolds range. The Reynolds numbers of the order of 100 000 are still in the region of strong viscous effects, like laminar bubbles and early separation, so some notable dependence of FoM on Re was expected. Some not entirely monotonic increase of FoM with Re is observed, but the result is influenced by the measurement error, especially for the second measured Re. The measurement was repeated 6 times to obtain also some data for standard deviation. Higher standard deviations are encountered towards lower Re, this is probably due to increased relative error as smaller part of the load cell capacity is used - see Fig. 7. No clear influence of the propeller distance can be deduced from the results.

4.4 Influence of rpm ratio

In Fig. 8 and 9 the FoM is plotted together with non-dimensionalised thrusts and torques. The rotational rate ratio $R_{RR} = n_1/(n_1 + n_2)$ is used for the x-axis. When both propellers have the same speed of rotation, the rotational rate ratio reaches $R_{RR} = 0.5$.

Figure 7: Percentage of load cell capacity used in the FoM vs. Re experiment

Figure 8: performance results - variable rpm ratio, distance between propellers 0.07 D
The results for different propeller distances are almost identical. To able to compare them more effectively, they are plotted in the same figure Fig. 10. Both cases have the maximum FoM asymmetrically placed towards the right i.e. \( n_1 > n_2 \). For propeller distance 0.14 D, the maximum FoM=0.745 is reached for \( R_{RR} = 0.563 \) which means that the first propeller rotates 28% faster. This is due to the fact that the propellers were designed for non-static conditions.
4.5 Acoustic measurement

One of the negative impacts of the contra-rotating setup is a relatively higher noise compared to single propeller with equivalent thrust. For the current experiment NTI XL2 audio analyzer with M2211 measurement microphone was used for obtaining sound pressure levels (SPL). As can be seen in Fig. 11 and 12 the rpm of the second propeller plays the most important role in the overall noise in this case. The sound spectrum for the case of $n_1 = n_2$ (blue line) shows the blade passing frequency at twice the rotational rate as expected and higher harmonics follow. The red line $n_1/(n_1 + n_2) = 0.3125$ however show a massive peak at approximately double the frequency of rotation of the second propeller. More tests and deeper analysis will be needed for a better understanding of the noise generated by contra-rotating propellers.

![Figure 11: Sound pressure level vs. rotational rate ratio](image1)

![Figure 12: Spectrum for two selected rotational rate ratios](image2)

5 Conclusion

The presented data serve two main purposes. One is to evaluate the measurement possibilities of the newly designed test rig and discover possible faults and defects. The other purpose is to provide validation data for numerical model of contra-rotating propellers being developed in parallel to this project. The fact that the propellers were designed for non-static conditions and are now used for static thrust scenario means that the numerical model can be validated also for off design conditions. Future plans of improving the test rig includes measurement of static and dynamic pressure in the vicinity of the propellers to be able to use different definitions of Figure of Merit and compare the results. Another big task is to modify the whole rig for dynamic measurements in a wind tunnel. Also non-axial free-stream velocity experiments are planned in order to simulate the behaviour of a drone flying sideways.

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References


