SIMULATION OF PROPELLER EFFECT IN WIND TUNNEL

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Keywords: *propeller effect, wind tunnel, simulation, aerodynamic characteristics*

Abstract

Significance of the influence of operating propellers on aircraft aerodynamic characteristics is well-known. Wind tunnel testing of an aeroplane model with operating propellers is a complex task regarding the required similarity of the full-scale and the model case. Matching sufficient similarity in axial and rotational velocities in the propeller slipstream is the primordial condition for the global aerodynamic similarity of the wind tunnel testing. An example of the model power units with related devices is presented. Examples of the wind tunnel testing results illustrate the extent of propeller influence on aerodynamic characteristics of a generic aircraft.

1 Introduction

The simulation of the propeller effects is an important part of the wind tunnel testing of an aeroplane. Both the importance and the complexity of the simulation are given by the fact that the aerodynamic phenomena connected with propeller are very complex including complex interactions between the propeller(s) and the airframe.

2 Nomenclature

b	wingspan [m]
C_L	lift coefficient [–]
C_{L0}	lift coefficient at α=0° [–]
C_l	rolling moment coefficient [–]
C_m	pitching moment coefficient [–]
C_n	yawing moment coefficient [–]
C_Q	torque coefficient related to $\rho\ n^2 d^5$ [–]
C_T	thrust coefficient related to $\rho\ n^2 d^4$ [–]
d	propeller diameter [m]
J	propeller advance ratio [–]
n	propeller revolutions per second [s^{-1}]
Q	propeller axial torque moment [N.m]
Qc	torque coefficient rel. to $1/2\ \rho\ V^2 Sb$ [–]
S	aeroplane wing area [m^2]
T	propeller axial thrust [N]
T_c	thrust coefficient rel. to $1/2\ \rho\ V^2 Sb$ [–]
V	airspeed [$m.s^{-1}$]
α	angle of attack [°]
β	sideslip angle [°]
ρ	air density [$kg.m^3$]
$_{FS}$	full scale
$_{M}$	model
$_{CRP}$	counter rotating propellers

3 Motivation

The importance of the influence of the operating propeller power units on aircraft aerodynamic characteristics is well-known. The propeller units create both direct effects caused by the forces acting directly at the propeller (thrust, normal force, torque moment) and indirect effects caused by the significant aerodynamic influence on the aircraft and on the flow circumventing the airframe [1]. This influence is caused primarily by the interaction of the propeller slipstream with other parts of the aircraft.

It is also evident that the influence depends essentially on the power output of the power unit; the higher power output, the higher direct forces but also the higher "indirect" aerodynamic influence as the strength of the slipstream is related to the forces created at the propeller. The power is frequently usefully to relate to the size of the aircraft, the relation can be conveniently expressed for example using power-to mass ratio of an aircraft. The effects of the propeller on the wing or on the whole aircraft are well-described in the case of the conventional propeller-driven aeroplane configuration, i.e. in the case of a single-engine aeroplane with propeller on the nose of the fuselage.

As both direct and indirect propeller effects influence not only the aircraft aerodynamics but also its flight dynamics behaviour as one of main consequences, the simulation of the propeller effects at wind tunnel testing of an aeroplane is therefore very important. Especially the influence on aircraft stability and controllability can be crucial.

4 Theory of similarity

4.1 Propeller effects

The most significant direct and indirect effects are as follows.

Direct effects

- Thrust in the axis of the propeller
- Normal force in the plane of rotation of the propeller
- Torque moment of the propeller

Indirect effects of the propeller slipstream

- Effect on the moments of the wing
- Effect on the lift of the wing
- Effect on the downwash and the crossflow at the tail unit
- Effect on the dynamic pressure at the tail unit

The simulation of the propeller slipstream for a constant-speed propeller requires matching both the slipstream axial velocity-to-airspeed and the slipstream rotational velocity-to-airspeed ratios [3]. But to match these both ratios over the entire range of the aeroplane lift coefficients would require an adjustable pitch propeller, in ideal case adjustable “in flight” during testing run that is a very challenging issue.

However, a satisfactory approximation of the real slipstream can be accomplished with a single setting of a propeller pitch (or few pitches) over a large part of the lift coefficients, so manually “on ground” adjustable propeller is adequate.

From propeller momentum theory, it can be found that the axial velocity ratio can be matched with a propeller of scale diameter. The rotational velocity ratio can be matched with geometrically similar propeller operating at the proper advance ratio. To match required similarity in the thrust and torque, the equality of the full-scale T_{cFS} and the model T_{cM} and of the Q_{cFS} and Q_{cM} coefficients shall be matched.

It is possible to deduce, if the full-scale and model propellers are geometrically similar, that for a given propeller advance ratio, the similarity of the thrust is preserved at T_{cM} equal to T_{cFS}. In a similar manner, the similarity of the torque moment is preserved at Q_{cM} equal to Qc_{FS}.

The stated conditions of similarity suppose that the geometrically similar propellers, at a given advance ratio, have identical C_{TFS} and C_{TM} (and analogically C_{QFS} and C_{QM}) coefficients, which is not exactly matched in reality because of very different propeller Reynolds numbers and different propeller Mach numbers [2]. The model to full-scale Reynolds numbers ratio is given by the ratio of the wind tunnel flow velocity to the flight airspeed multiplied by the geometric scale factor, the Mach numbers ratio is given by the ratio of the wind tunnel flow velocity to the flight airspeed. But the differences in the thrust and torque coefficients are usually acceptable from the practical point of view if the low-speed testing is performed in the linear region of the propeller characteristics (i.e. in the linear regions of C_T vs J and C_Q vs J curves).

Another problem can arise from the fact that it can be impossible to create geometrically similar model propeller for manufacturing and/or strength reasons. The relative thickness of the propeller blades is frequently low (in the order of several percent) and thus it can be impossible to use exact scaled-down thickness on the model propeller. In this case, the model propeller with thicker blades can be designed; that is aerodynamically similar in the operational range of thrust and torque coefficients, the diameter of the propeller, the diameter of the propeller hub and the numbers of the blades are still kept.

4.2 Model and testing device

An experimental wind tunnel testing was performed with a generic model of a general aviation monoplane with two engines. To emphasize the effects connected with the propeller, the propeller diameter was relatively big and the thrust coefficient of the power units relatively high. The propellers could rotate either in the identically oriented senses (the both clockwise viewed from the rear) either in counter-rotating mode (the left propeller clockwise, the right propeller counter-clockwise).

The model propellers were driven by electric motors built in the models of the engine nacelles. The model propeller has a diameter of 0.4 m and was powered by electric engines with a maximum power of 16 kW at 11 000 rpm.

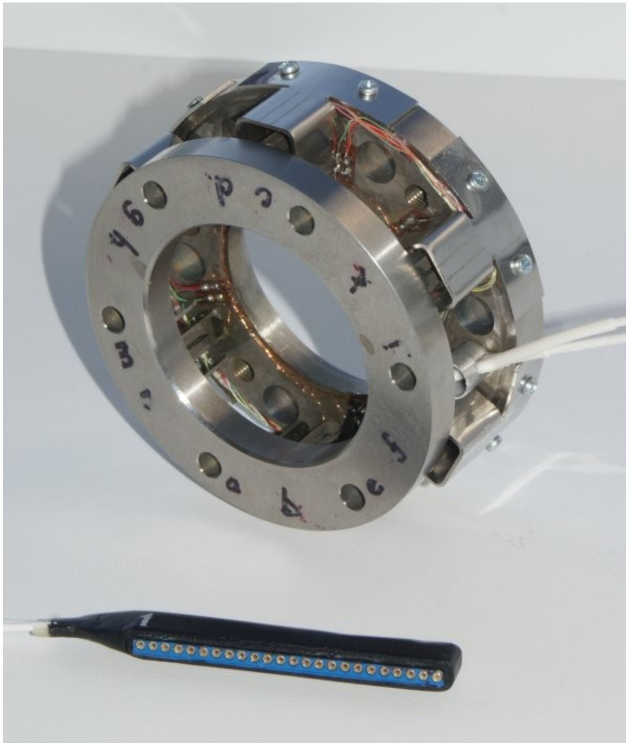

Fig. 1. Torque strain gauge balance

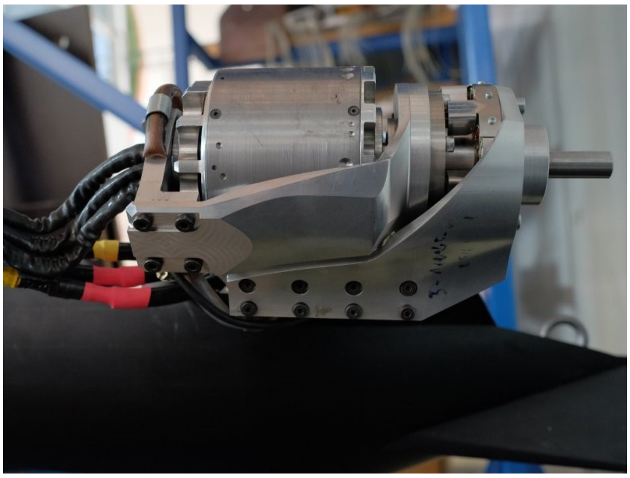

Fig. 2. Model power unit including two component strain gauge balances (thrust and torque)

The motor equipped with propeller was hinged on the strain-gauge balance built in the model engine nacelle. The balance of the left power unit measured the thrust and the torque moment, the balance of the right unit measured the thrust. The independent measurement of the thrust and the torque moment of the power units enabled better evaluation of the influence of the power units on the aircraft and better evaluation of the effectiveness of the concept of installation of the power units as the thrust source of the aircraft.

5 Results

The results of the wind tunnel testing are presented in Fig. 3 to Fig. 7. The testing with operating propellers was performed at Reynolds number 1 million related to the wing mean aerodynamic chord. The thrust coefficient of one propeller T_c was kept constant regardless the angle of attack of the airplane model. The advance ratio of the propellers during the run was constant and equal to values within a range of 0.7 to 1.6.

6 Discussion

6.1 Influence of propellers on lift

Detectable difference was observed between the two cases of the propeller rotation. The slope of the both lift curves was almost identical, but C_{L0} for the counter-rotating propellers was slightly lower, $\Delta C_{L0} \approx$ -0.025. The explanation was probably in the flow over the horizontal tailplane, as its right side was influenced mainly by counter clockwise rotating propeller which rather decreased the angle of attack.

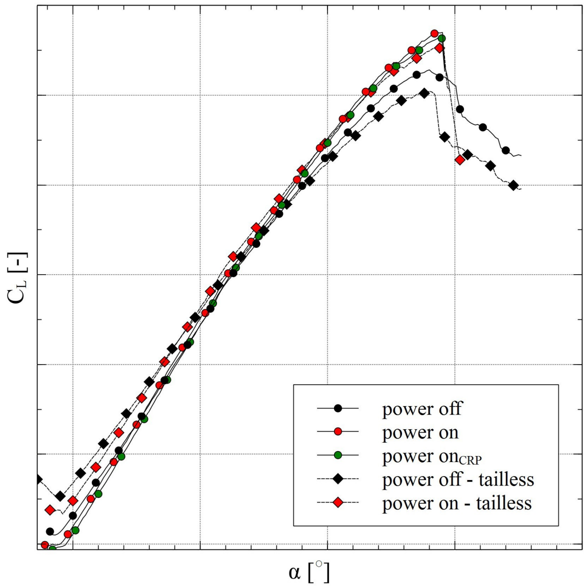

Fig. 3. Lift curves

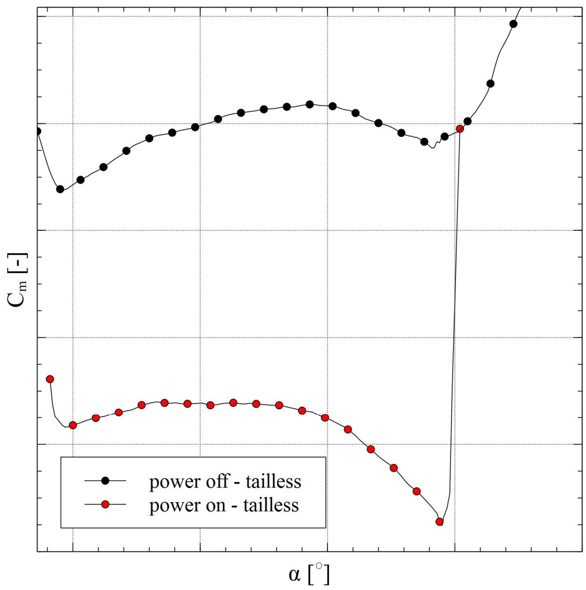

Fig. 4. Moment curves of tailless aircraft

6.2 Influence of propellers on static longitudinal stability of aeroplane without horizontal surface

It was supposed that the indirect influence on the wing was limited at this type of the aeroplane configuration, so that the observed differences were caused mainly by the direct effects especially the thrust of the propellers. The direct effect was primordial, pronounced by the difference in the pitching moment in the order of $\Delta C_m \approx -0.5$. However, the curves were not equidistant; they differed also by their slope so secondary indirect aerodynamic influence with longitudinally stabilizing effect had to be also present. The neutral point moved backwards by approximately 5.5 percent of the mean aerodynamic chord. The changes of the forces created on the propellers with increasing angle of attack caused by the gradually inclined flow acting on the propeller.

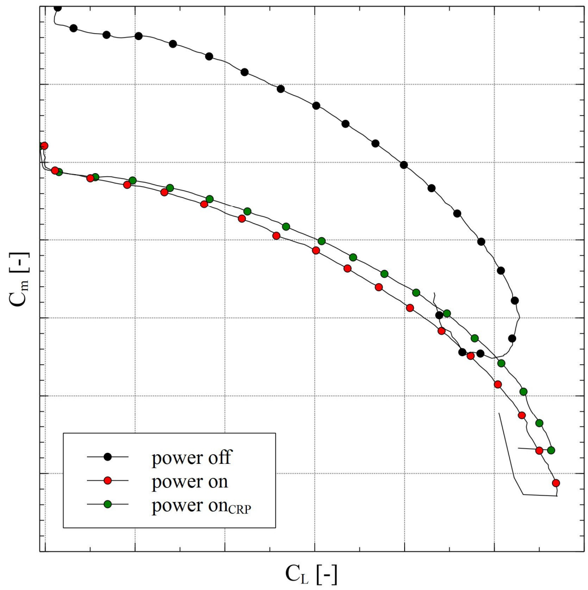

Fig. 5. Moment curves of complete aircraft

6.3 Influence of propellers on static longitudinal stability of complete aeroplane

The influence of the rotating propellers on the horizontal tailplane pronounced as longitudinal destabilization of the aeroplane. The neutral point moved forward by approximately 4.5 percent of the mean aerodynamic chord with the propellers rotating in the identical senses, and by approximately 6 percent with the counter-rotating propellers. With respect to the fact that the propellers had influence to the contrary for the configuration without the horizontal tail, it seems possible to deduce that there was very significant influence of the propellers on the horizontal tail. The propellers created such changes in the flowfield that in consequence led to the decreasing of the angle of attack of the horizontal tailplane and thus to the diminution of its lift (with respect to the convention that positive lift was directed "upwards"). This influence is even more pronounced for the counter-rotating propellers.

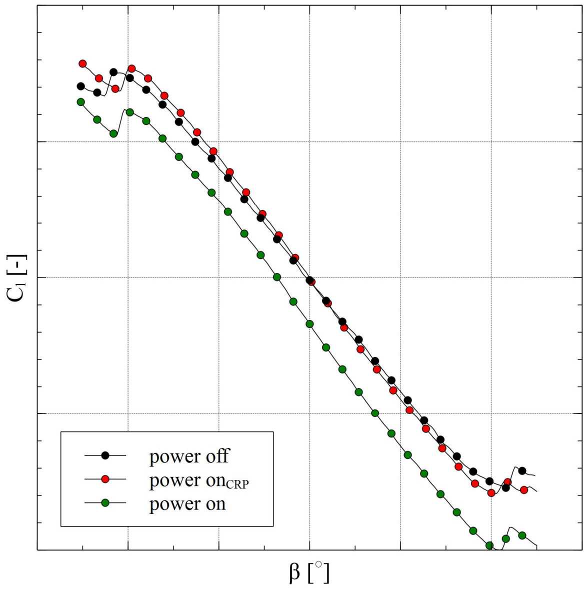

Fig. 6. Rolling moment coefficient

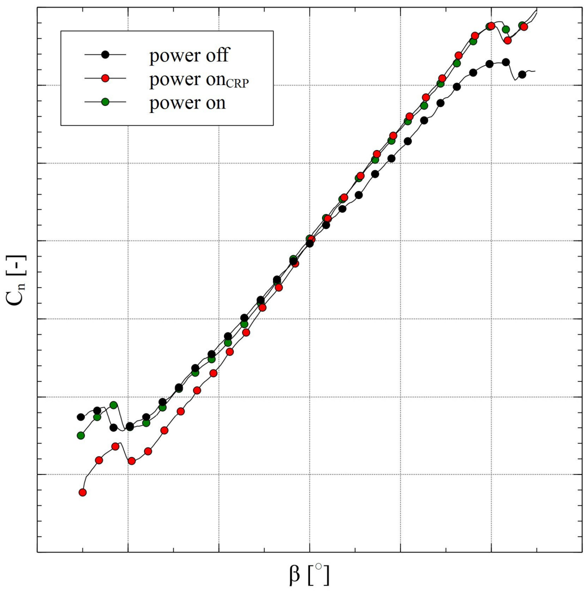

Fig. 7. Yawing moment coefficient

6.4 Influence of propellers on static lateral-directional stability

The rotation of the propellers increased the "lateral stability", i.e. increases the absolute value of the derivative of the rolling moment with respect to the sideslip angle. The increase was approximately 11 percent with both propellers rotating clockwise and 7.5 percent with the counter-rotating propellers. The probable reason is the difference between force components at the left and right propellers discs created as a result of combination of the angle of attack and the sideslip angle. This phenomenon was slightly supressed by the counter-rotating propellers. The reaction torque moment of the clockwise rotating propellers also caused the negative rolling moment at the zero sideslip angle. The moment was relatively high as its value corresponded to the sideslip of 4.5 degrees. The influence of the propellers on the derivative of the yawing moment with respect to the sideslip angle was also highly pronounced, and the propeller operation significantly increased its value also in this case. The increase was approximately 13 percent with the propellers rotating clockwise and nearly double value (24 percent) with the counter-rotating propellers. The reasons were higher dynamic pressure on the vertical tail unit and the side force component at the propeller discs created as a result of sideslip.

6.5 Influence of the type of rotation of the propellers

As resulted from the previous analysis, the type of rotation of the propellers is not negligible, but its significance is moderate. Nevertheless, the differences between the propellers rotating in the identical senses and the counter-rotating propellers were registered in the all studied relations. Probably the most important from the point of view of the flying qualities was the difference in the static longitudinal stability where the counter-rotating propellers manifested even more destabilizing effect than the propellers rotating in the identical senses. On the contrary, the counter-rotating propellers naturally did not cause the aerodynamic asymmetries at the zero sideslip angle, that were registered mainly at the roll moment with the propellers rotating in the identical senses.

7 Conclusions

The prediction of the propeller effect on aircraft aerodynamics is a fundamental part of the aircraft development phase, especially from the aerodynamics and flight mechanics point of view. This issue is quite demanding, since the computational methods are rather less reliable, while the experimental research is quite difficult. Nevertheless, the experiment is considered as a necessity in case of somehow different aircraft projects. There is notable lack of reliable data in this field of research for many reasons.

The integral aerodynamic characteristics of the airplane model with the power unit on (including variant with counter-rotating propeller) and off were examined, as well as changes of the stability characteristics and thrust and torque produced by the propellers. The results make possible better prediction of a propeller power effect and can be also used for CFD approaches validation.

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