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Rotor theories by Professor Joukowsky: Momentum theories

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ABSTRACT

This paper is the first of two papers on the history of rotor aerodynamics with special emphasis on the role of Joukowsky. The present one focuses on the development of the momentum theory while the second one surveys the development of vortex theory for rotors. Joukowsky has played a major role in these developments. Although he cooperated with other famous aerodynamicists like Prandtl, his contribution is not well recognized as most of his publications are in Russian. The paper discusses the role of the English, Russian and German research schools in the beginning of the Twentieth Century, and the contributions by individual researchers like Lanchester, Prandtl, Betz and Joukowsky himself. After the one-dimensional momentum theory was well established, the introduction of torque and angular momentum was the next step. Joukowsky has led the basis for this step, but Glauert's Blade Element Momentum still is the basis of current rotor design codes. He applied some assumptions limiting the validity to moderate and high tip speed ratios. Sørensen and van Kuik published a solution for wind turbines with very low tip speed ratios, which is now expanded to propellers as well, with one remaining assumption of inviscid flow. For very low tip speed ratios the general momentum theory gives unphysical results which disappear after applying a perturbation parameter representing phenomena not captured by the Euler equations.

Contents

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1. Introduction

This review, resulting from compiling several smaller articles, is dedicated to the 100-year anniversary of the publication of the vortex concept for rotor theory by Professor N.E. Joukowsky.[1] During 1912–1918 he published the legendary cycle of four articles on "The vortex theory of screw propeller" [1–4]. The first report of his famous theory was made on October 1, 1912 as a presentation to the Moscow Mathematical Society and the respective article was dated as 1912, too, although, according to Vetchinkin [5], the real publication was not received by readers until the beginning of 1913. In celebration of this date we write about the development and implementation of the famous rotor theory. Our collection of Joukowsky's heritage and new results in the development of his rotor theory results in a large document which has been divided into two articles with the overall title "ROTOR THEORIES BY PROFESSOR JOUKOWSKY" with a subtitle for the first part of "Momentum theories" and for second one of "Vortex theories". Nevertheless, we should point out here that our separation is quite relative, because both theories use elements of each other. To be more correct, we should say that the first article is devoted to the case of rotors with infinite number of blades and the second article to the case of rotors with finite number of blades.

This introduction presents a global overview of the history of rotor aerodynamics and Joukowsky's role in this. In Section 2 of the current article, we remind our readers about the important role of Professor Joukowsky in aerodynamics in the context of the history of rotor theory. In the second section, we offer a retrospective of early rotor aerodynamics and clarify the role of Joukowsky [6] in the derivation of an important result about maximum wind power conversion efficiency (59.3%) which was wrongly named earlier as the Betz limit, incorrectly acknowledging only the contribution of Betz [7]. The third section presents the most important steps in the development of a general momentum theory for rotors, which is continued in Section 4 where the final result is presented. Furthermore, the last section provides some applications of the actuator disk theory and our criticism of numerous incorrect theories where the authors claim to exceed the classical Betz–Joukowsky limit.

The second article in this series will be devoted to a blade element theory to emphasize the development of the Kutta–Joukowsky theorem with a special consideration of the rotor vortex theory, the formulation of which became a significant achievement by Professor Joukowsky. In the context of this contribution, a major element of our work and a significant development of Joukowsky's heritage is a description of the first complete analytical solution of the equations describing the NEJ rotor (named after his initials) with a finite number of blades and a first comparison with a rotor of the Betz type proposed by the German school.

1.1. Stages in the development of rotor aerodynamics

The development of research in rotor aerodynamics (screw propeller, propeller, wind turbine, helicopter, etc.) has always been associated with an intensive development of the appropriate branch of industry. The first attempts to solve problems of steamship navigation using screw propellers should be considered as starting point for the elementary rotor theory. This resulted in the simple Rankine-Froude one-dimensional momentum theory of the screw propeller, called also one-dimensional slip-stream or actuator disc theory [8,9].

In the early 20th century, the development of rotor aerodynamics was motivated by the creation and intensive evolution of aviation. At that time, all famous aerodynamic research schools in England, Russia and Germany studied this subject, but the schools from Russia (N.E. Joukowsky with his pupil V.P. Vetchinkin) and Germany (Prandtl with his pupil A. Betz) dominated in the creation of new concepts for an optimum rotor (Fig. 1). Their work, as well as efforts of their contemporaries, resulted in the development of the blade element momentum (BEM) theory to design rotor blades; in the creation of the general momentum theory of the actuator disc and in the formulation of a new vortex concept of rotor aerodynamics, which is suitable for analyzing the screw propeller with a finite number of blades [1–4,10].

After this intensive and fruitful period in the evolution of rotor aerodynamics for aviation needs, research activity somewhat weakened due to the movement of aircraft propulsion from rotor to jet. At this time, the research was mainly motivated by the need of the submarine navy and helicopter engineering to develop effective and low-noise screw propellers.

Current development of rotor aerodynamics is undoubtedly associated with the rapid progress of wind energy, which has transformed from the minor performance capabilities of an alternative energy with separate wind turbines to a main branch of the power economy as the most important renewable source of global energy. During the last few decades, wind turbines have been installed in large wind farms. At the beginning of the 20th century, the industrial breakthrough of wind energy is purely comparable to the rapid progress of nuclear power engineering during the second half of the last century, and most likely will surpass it. Indeed, for example, in 2013 the energy produced by wind turbines in Denmark was 31% of the total electric energy generated, in Portugal – 23%, Spain – 21%, Germany – 8%. Further growth is proposed up to the level of 50%, moving wind energy towards the level of the main energy producers.

In response to the needs of the industry, the interest of researchers in rotor aerodynamics has grown significantly. Today a new stage of intensive scientific development, similar to the fruitful aviation era led by the scientific schools of Joukowsky and Prandtl, is underway. State-of-the-art advances are occurring in the creation of numerical simulation tools for rotor optimizations, modeling of wind turbine wakes and establishing of numerical aerodynamics of wind farms [11,12]. Without question, the state-of-the-art of rotor aerodynamics has been advanced significantly due to the success of modern computational fluid dynamics (CFD) with which engineering rules have been developed and verified for most unsolved problems. Airfoil data for blade design are now derived from experiments and CFD computations using new techniques to

[1] Alternatively spelled as Zhukovskii, Joukowski, Joukovskii or Žukovskij etc.