Progress in Aerospace Sciences 55 (2012) 17–45

Contents lists available at SciVerse ScienceDirect

Progress in Aerospace Sciences

journal homepage: www.elsevier.com/locate/paerosci

A review of the Magnus effect in aeronautics

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ARTICLE INFO

Available online 14 September 2012

Keywords:
Magnus effect
Rotating cylinder
Flettner-rotor
Rotor airplane
Boundary layer control

ABSTRACT

The Magnus effect is well-known for its influence on the flight path of a spinning ball. Besides ball games, the method of producing a lift force by spinning a body of revolution in cross-flow was not used in any kind of commercial application until the year 1924, when Anton Flettner invented and built the first rotor ship *Buckau*. This sailboat extracted its propulsive force from the airflow around two large rotating cylinders. It attracted attention wherever it was presented to the public and inspired scientists and engineers to use a rotating cylinder as a lifting device for aircraft. This article reviews the application of Magnus effect devices and concepts in aeronautics that have been investigated by various researchers and concludes with discussions on future challenges in their application.

Contents

Abbreviations: AoA, Angle of Attack; DOC, Direct Operating Costs; MAV, Micro Aerial Vehicle; MRO, Maintenance, Repair and Overhaul; MSBC, Moving Surface Boundary Layer Control; MTOW, Maximum Take Off Weight; OWE, Operating Weight Empty; RPM, Revolutions Per Minute; URANS, Unsteady Reynolds-Averaged Navier-Stokes; STOL, Short Take Off and Landing; VTOL, Vertical Take Off and Landing

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0376-0421/$ - see front matter
http://dx.doi.org/10.1016/j.paerosci.2012.07.001

1. Introduction

Very few devices based on the Magnus effect have attracted attention or were crowned by success. On the other hand, its potential benefit compared to other airfoil-based lifting devices, such as a high lift coefficient, inspired engineers to develop devices for extracting wind energy, to propel and to steer vessels and ultimately to lift an airplane. Many research results on rotating cylinders were presented in the literature which focus mainly on the generation of aerodynamic forces. To review Magnus effect applications in aeronautics, the scientific literature is surveyed in this paper as well as newspaper articles and patent specifications in order to illustrate the whole context.

In this paper the Magnus effect is defined as a device that provides a moving wall on its body to influence the boundary layer around the device, in order to produce a lifting force perpendicular to the flow direction. A rotor airplane is defined as an airplane which uses the Magnus effect for lift generation. Similar devices which generate a lifting force due to blowing or suction are not taken into account here (e.g., the Alcyone of Jacques Cousteau using Turbosails). Many ideas are published in the literature on how to use the Magnus effect in naval or aeronautical applications. Only a few ideas led to innovations. In this paper a brief history of Magnus effect research is presented, followed by a discussion of ideas and concepts for the required propulsion of a Magnus rotor, for a combination of different lifting devices, and for an enhancement of the Magnus effect. Details on the flight physics of a Magnus rotor are given and the aerodynamic characteristics and gyroscopic effects are highlighted. Successes and failures in the application of Magnus effect devices in aeronautics are discussed. A few examples of full size rotor ships and rotor airplanes are presented, to point out that there are still technology gaps to overcome. This is followed by a discussion of aircraft conceptual design and stability and control aspects. Finally the unique characteristics of a Magnus effect device are discussed which offer operational advantages for an airplane and therefore may justify the design of a new rotor airplane configuration. Concluding remarks on recent advances in Magnus rotor technology in the modern day context complete this review.

1.1. History

Isaac Newton is said to have been the first to explain the motion of a tennis ball in relation to its spin. In his letter to Oldenburg in 1671, writing about the dispersion of light, he explained "I remembered that I had often seen a tennis ball struck with an oblique racket describe such a curved line. For a circular as well as progressive motion being communicated to it by that stroke, its parts on that side where the motions conspire must press and beat the contiguous air more violently, and there excite a reluctancy and reaction of the air proportionately greater" [1,2].

At the beginning of the 19th century, the common understanding in the field of gunnery was that the flight path of a shell or a bullet "is nearly described by the curve of a parabola, and consequently, that the resistance of the air to the motion of these bodies is altogether inconsiderable" [3]. In 1805, Benjamin Robins stated in his paper *Resistance of the air* that a bullet always acquires a whirling motion and a progressive one and therefore he concluded that the air resistance "will be increased in that part where the whirling motion conspires with the progressive one" [3]. Hence, the deflection in motion was attributed to the difference in air resistance, and should be called the *Robins effect* since that time [4].

Gustav Magnus was a Professor of Physics at the University of Berlin during the years 1834 to 1869. His well-known experiment was conducted in 1852. It consisted of a brass cylinder held between two conical bearings to which he could impart a high speed of rotation by means of a string. He mounted the cylinder upon a freely rotatable arm and directed a current of air from a blower towards it (Fig. 1). When the cylinder was rotated, he noticed a strong lateral deviation. The spinning body always tended to deflect toward the side of the rotor that was traveling in the same direction as the wind coming from the blower. The magnitude of the deflecting forces was not measured by Magnus at that time [5]. From now on, the phenomenon was called *Magnus effect*.

In the year 1877 Lord John Rayleigh wrote an article *On the irregular flight of tennis balls* [6]. He attempted to explain the curved path of a ball in terms of the Magnus effect by calculating the Magnus force from the pressure distribution of a rotating body. At that time he also stated that it was not possible to give a complete mathematical formulation of the actual physical process since no mathematical methods were available to express the manner in which friction between the fluid and the rotating cylinder would produce circulation.

Lafay reported in 1912 about his investigations in the laboratories of physics of Ecole Polytechnique and in the Etablissement d'aviation militaire de Vincennes. He conducted experiments and demonstrated that with rotating cylinders one may attain several times the output in lift of a plane surface having the same projected area. His measurements showed how pressure and