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Technical and functional analysis of Spanish windmills: 3D modeling, computational-fluid-dynamics simulation and finite-element analysis

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ABSTRACT

A detailed study has been made of the two typologies of windmills in Spain, specifically the rectangular-bladed type, represented by the windmill 'Sardinero', located near the town of Campo de Criptana (Ciudad Real province, Spain) and the type with triangular sails (lateens), represented by the windmill 'San Francisco', in the town of Vejer de la Frontera (Cádiz province, Spain). For this, an *ad hoc* research methodology has been applied on the basis of three aspects: three-dimensional geometric modeling, analysis by computational-fluid dynamics (CFD), and finite-element analysis (FEA).

The results found with the CFD technique show the correct functioning of the two windmills in relation to the spatial distribution of the wind velocities and pressures to which each is normally exposed (4–7 m/s in the case of 'Sardinero', and 5–11 for 'San Francisco'), thereby validating the operative functionality of both types. In addition, as a result of the FEA, the spatial distribution of stresses on the rotor has revealed that the greatest concentrations of these occurs in the teeth of the head wheel in 'Sardinero', reaching a value of 12 MPa, and at the base of the masts in the case of the 'San Francisco', with a value of 24 MPa. Also, this analysis evidences that simple, effective designs to reinforce the masts absorb a great concentration of stresses that would otherwise cause breakage. Furthermore, it was confirmed that the oak wood from which the rotors were made functioned properly, as the windmill never exceeded the maximum admissible working stress, demonstrating the effectiveness of the materials used in this period.

1. Introduction

The management and use of wind energy has produced a great quantity of tangible and intangible remains that constitute the historic heritage of this energy source, windmills being one such manifestation. However, the exact origins have not been identified, and it remains uncertain whether they arose in the Greco-Roman world or are related to Oriental inventions (Arab or Chinese cultures) transferred to the Mediterranean area by the Islamic culture and specifically to Europe in the Middle Ages during the Crusades [1].

These devices are intended to convert wind energy into mechanical energy by the movement of a windwheel, which in turn activates a system of horizontal rotation (axis), thereby moving a system of vertical rotation by a system of gears (head wheel and pinion) that in turn transfer a circular movement to the millstones for grinding cereals. In some cases, the same system is used to raise water from wells. Also, they are located in areas with the strongest air flows, mainly hilltops or rises in the terrain. This system is widespread in Spain [2].

In addition, new interest is awakening in these systems due to the simplicity of their design and thus their low cost, given that they also offer a high ratio of energy generation at low wind velocities.

To understand the technology of these ancient windmills, several monographs have been published that point out in detail the theory of Betz on slow wind machines (as were the ancient windmills) and analyze its optimum performance to take advantage of the maximum available wind power [3–8]. Also, a thorough search has been made, finding only some work done on windmills in general and Spanish in particular, with different approaches. Moreover, it has been conducted studies on industrial archeology or simply descriptive typologies of windmills in Spain [9–11], about the introduction of European wind- and watermill technology by the Dutch in Asia [12], on three-dimensional geometric model of a type of a Manchegan windmill through techniques of engineering graphics [13], performed the mechanical study about power and developed couple for two windmills triangular sails [14,15], or compared the two types of Spanish windmills from that

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Nomenclature

u_i	components of the velocities in the main directions of the space x_i (m/s)
u'_i	components of the fluctuating velocities (m/s)
t	time (s)
ρ	air density (kg/m^3)
p	pressure (Pa)
μ	dynamic viscosity (cP)
δ_{ij}	Kronecker delta function
k	turbulence kinetic energy (m^2/s^2)
ω	specific turbulence dissipation rate (1/s)
$\widetilde{G}_k$	generation of the k due to the mean velocity gradients
G_ω	generation of ω
Γ_k	effective diffusivity of k
Γ_ω	effective diffusivity of ω
Y_k	dissipation of k due to the turbulence
Y_ω	dissipation of ω due to the turbulence
D_ω	cross-diffusion term
S_k & S_ω	user-defined source terms

mechanical perspective [16]. Also, there are published mechanical studies on Cretan windmills that deal with the study of power developed on the device [17,18] or on the design and performance of the rotor [19] in different operating conditions. Finally, studies to perform the analysis of the structure and movement of the sails in a large Chinese windmill [20], or detailed studies of the aerodynamics of the sails in different operating conditions [21,22] have been found.

However, no functional analysis using the techniques of computational-fluid dynamics (CFD) or finite-element analysis (FEA) is available. These functional analyses with the CFD and FEA techniques treat a key feature not covered in conventional technical studies, which, based on the data from wind survey of an area where the windmills are located, include an examination of the torque and the power generated by the wind device.

Thus, the aim here is to present a thorough technical and functional analysis that provides detailed information concerning the technological characteristics of the two types of windmills found in Spain: one with rectangular blades, and one with triangular sails. For this, the work is divided into the following sections: Section 2 offers a detailed description of the windmills studied, highlighting their historical importance and the technology used; Section 3 describes the methodology used in the study, specifically in the phase of 3D geometric documentation and the simulation by the CFD and FEA techniques; Section 4 offers the results and discussion; and finally, Section 5 presents the conclusions drawn.

2. Windmills in Spain

Although different typologies of windmills are scattered around the world, it bears differentiating between those having a vertical or a horizontal axis. Among the latter, undoubtedly more widespread, there are fundamentally three types: the Nordic or pivot, with tripods constructed over rough walls, and Mediterranean windmills than may have either rectangular blades or triangular lateen sails [23]. In particular, in Spain, windmills are of the Mediterranean type, known as tower or rotating-cap windmills, as the blades or sails are aligned with the dominant wind direction by turning the conical roof through the action of the guide pole.

For the present study, two horizontal-axis windmills were selected as representative of the typologies present in Spain: the rectangular-blade windmill 'Sardinero', located in the town of Campo de Criptana (Ciudad Real province), and the triangular-sail windmill 'San Francisco', situated in Vejer de la Frontera (Cádiz province).

2.1. Historical importance and characteristics of the windmills chosen

The historical importance of the windmill of 4 rectangular blades 'Sardinero' lies in its being one of the most representative examples of this typology in Spain, located in La Mancha (the type of windmill that appears in the Spanish literary masterpiece *Don Quixote*) and officially catalogued by the Spanish government as an Item of Cultural Interest (Bien de Interés Cultural; BIC, BOE 11 de octubre de 2001) under the category of Historical Site. Therefore, this monument is protected, preserving the original structure and mechanism from the 16th century. Furthermore, it appears in the Registry of the Marqués de la Ensenada of 1752 under another name and was restored in 1878.

This windmill (Fig. 1) is composed of a cylindrical tower 8.14 m high with a rotational conical roof (called a cap) of 3.64 m high. This makes the windmill the highest of its type in Spain, with an overall height of 11.78 m, measured from the circular foundation of 6.03 m in diameter. In addition, it has 3 distinct levels (ground floor or stable; intermediate floor or cabin; and upper floor or milling room), and 12 small windows in the upper floor for the miller to be able to determine the predominant wind direction and correctly orient the windwheel by turning the cap with the use of the guide pole. In addition, as the most representative elements, the windshaft (rotating axle) measures 7.13 m long, the head wheel has a diameter of 2.60 m, and each blade 7.37 m has a total length from end to end of 16.30 m. With the total length of the blades, their rotation makes a circumference with a radius of 8.15 m and a circular sweep area of 208.67 m^2. Also, given that each rectangular blade has an exposed surface area of cloth (canvas) of 13.78 m^2 (the blades always being covered), the total cloth-covered surface area exposed to the wind was only 55.12 m^2.

The windmill 'San Francisco', of 8 triangular sails, was built between 1860 and 1865 and represents the typology typical of

Fig. 1. Windmill 'Sardinero' (Campo de Criptana, Ciudad Real province, Spain).