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A semi-empirical airfoil stall noise model based on surface pressure measurements

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ABSTRACT

This work is concerned with the experimental study of airfoil stall and the modelling of stall noise. Using pressure taps and high-frequency surface pressure microphones flush-mounted on airfoils measured in wind tunnels and on an operating wind turbine blade, the characteristics of stall are analyzed. This study shows that the main quantities of interest, namely convection velocity, spatial correlation and surface pressure spectra, can be scaled highlighting the universal nature of stall independently of airfoil shapes and flow conditions, although within a certain range of experimental conditions. Two main regimes for the scaling of the correlation lengths and the surface pressure spectra, depending on the Reynolds number of the flow, can be distinguished. These results are used to develop a model for the surface pressure spectra within the detached flow region valid for Reynolds numbers ranging from 1×10^6 to 6×10^6. Subsequently, this model is used to derive a model for stall noise. Modelled noise spectra are compared with experimental data measured in anechoic wind tunnels with reasonably satisfactory agreement.

1. Introduction

Airfoil stall occurs when the streamlines of a fluid flow around an airfoil do no longer smoothly follow its contour (see Fig. 1). This results from the angle of attack (AoA), which measures the angle between the main flow direction in the far-field and the airfoil chord, becoming larger than a critical value. The flow separates from the airfoil surface as a recirculating region, usually initiating at the trailing edge, develops on the upper side of the airfoil section. It is a result of the adverse pressure gradient and the associated deceleration of the fluid along the convex airfoil surface. With increasing AoA, separation rapidly propagates over the entire airfoil chord yielding an abrupt loss of lift. Furthermore, at high Reynolds numbers the vortical structures within the separated flow region are unstable and the flow is turbulent.

Although an important flow characteristic, airfoil stall has been less intensively studied than attached flows. The main reason lies probably in the fact that engineering devices using aerodynamic lift (e.g. aircraft, fans, turbines, etc.) are commonly designed to operate outside stalled flow conditions since these usually have an unfavorable impact on their efficiency. One notable exception is a stall-regulated wind turbine for which stall is used to limit power production at high wind speeds. Early experimental studies date back to the rapid advances in aeronautics in the middle of the 20th century [1,2] and a number of empirical methods or simulation tools have been subsequently developed to predict stall occurrence [3,4]. Dynamic stall has been more extensively studied as it is an important phenomenon in aeronautical applications that can

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Fig. 1. Attached flow (left) and stalled flow (right) around an airfoil.

potentially trigger aero-elastic instabilities (see the review article by McCroskey [5]). More recently, the emergence of supercomputing allowed intensive numerical Large Eddy Simulations of the stall phenomenon [6,7].

As mentioned above, stall is characterized by turbulent vortices developing in the separated flow over the suction side of an airfoil and subsequently convecting into the wake. These vortices are interacting with the airfoil surface, leaving a footprint in the form of turbulent surface pressure (SP) fluctuations and are therefore producing noise. This type of mechanism is denoted as 'self-noise' in the aeroacoustic terminology since the vortices generated by the airfoil itself are responsible for the noise generation by interaction with the airfoil surface. It is more specifically referred to as airfoil stall noise, but also sometimes as separation noise when the flow remains attached on a significant part of the airfoil chord (as opposed to 'deep-stall' when the flow separation stretches over the entire chord). Airfoil stall noise has been investigated experimentally and acoustic measurements are usually performed in dedicated anechoic wind tunnels [8–14]. A few models have been devised, the most popular one probably being the so-called BPM model [8]. This model is based on acoustic measurements of a NACA-0012 airfoil and it is parametrized using measured boundary layer properties for this particular airfoil, such as boundary layer and displacement thicknesses. It is then assumed that the model can be extended to different airfoil shapes, assuming that identical boundary layer properties yield identical radiated noise. Moreau et al. [11] conducted measurements of a NACA0012 and a NACA65-1210 airfoil in the anechoic wind tunnel facility at ECL (Lyon, France). Using Curle's analogy they developed a simplified model based on the simultaneous measurement of the SP near the trailing edge to predict the far-field noise. In the same facility, Christophe et al. [12] conducted measurements of a so-called Controlled Diffusion airfoil and proposed models based on LES calculations of the incompressible flow and either on Amiet's or Curle's theories for predicting the far-field acoustic pressure. These two experiments were conducted at relatively low Reynolds numbers ($Re \approx 1.5 \times 10^5$) and therefore include flow features characteristics of bluff body aerodynamics with distinct vortex shedding phenomena. More recently, Schuele and Rossignol [13] studied aeroacoustic noise from a stalled DU-96-W-180 airfoil in the AWB wind tunnel in Braunschweig. They derived a model based on classical trailing edge noise theory [15,16] and tuned for the stalled conditions. Subsequently and in order to study lower frequencies that could not be measured acoustically, this experiment was conducted again by Suryadi and Herr [14] in the same wind tunnel, but this time the study concentrated on SP measurements in stalled conditions. Both experiments were conducted at a Reynolds number equal to 1.2×10^6. Finally, there have also been several attempts to simulate stall noise using hybrid RANS/LES combined with acoustic analogies or related techniques [12,17,7]. However, these methods are still very demanding in terms of computational resources and cannot yet be applied in an engineering design context. Nevertheless, these can prove very valuable for understanding the mechanisms behind stall noise generation and to validate engineering models.

In the context of wind turbine noise in which this work has been undertaken, a number of studies related to stall noise have been conducted [18–20]. A recent analysis of wind turbine field measurements has shown that stall is most probably related to intermittent amplitude modulation effects [21]. Although the present study mainly focuses on wind turbine applications, its results may be in principle applied to any blade or airfoil stall case for which flow conditions do not significantly depart from the experimental conditions considered herein.

The aim of this paper is to study the turbulent characteristics of stall and to develop an engineering semi-empirical model for stall noise. Since the present study is performed in the context of wind turbines, relatively high Reynolds number flows (i.e. $1 \times 10^6 < Re < 6 \times 10^6$) are considered. The analysis is based on a series of wind tunnel experiments as described in Section 2. Specific aerodynamic measurement data characterizing stall are briefly reported in Section 3. These are used later in the paper to identify stall and interpret additional measurement data. The turbulence characteristics of a stalled flow field useful for a noise model derivation, namely convection velocity, spatial correlations and SP spectra, are investigated in Sections 4, 5 and 6, respectively. The results of these analyses are used to develop a stall noise model in Section 7 which is validated against independent anechoic wind tunnel experiments in Section 8. Conclusions are drawn and possible improvements to the model are discussed in the last section.

2. Description of experiments

The experimental data used in this article were acquired during several measurement campaigns.

Firstly, measurements of four different airfoil sections were conducted in the LM Wind Power wind tunnel in Lunderskov, Denmark [22]. This tunnel is a classical closed-loop aerodynamic wind tunnel with a 7 m closed test section. It has a 1.35 m wide and 2.7 m high cross-section specifically designed for the testing of wind turbine airfoils with little blockage and limited streamline curvature and a maximum wind speed of 105 m/s. The turbulence intensity measured in the clean wind tunnel configuration was estimated to be around 0.1% [23,24]. All tested airfoil sections span the width of the tunnel and

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