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Unsteady aerodynamics of single and tandem wheels

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A R T I C L E I N F O

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A B S T R A C T

The major unsteady aerodynamic forces and major physics of a generic single wheel and tandem wheels are studied for the first time using wind tunnel tests. The wind-tunnel tests are performed in the 2.1 m×1.5 m wind tunnel at the University of Southampton. The tandem-wheel configuration consists of two in-line wheels that can be tested at different inter-axis distances and various installation angles. A vibration test is performed *in situ* on the model assembly to validate the unsteady-load measurements. Mean and unsteady aerodynamic loads and on-surface pressures are measured. Particle Image Velocimetry is used to acquire the velocity fields in the wake downstream of the model and surface oil-flow technique is used to identify the flow features on the surface of the wheels. Proper Orthogonal Decomposition is also used to characterise the wake in terms of unsteady fluctuations. The results of the experiments on the tandem wheels show that higher values of inter-axis distance correspond to slightly higher total mean drag coefficients and remarkably lower drag coefficient RMS values. Higher installation angles are associated with higher mean drag coefficients but generally lower fluctuations of the force coefficients. Non-zero mean lift coefficients are found for low inter-axis distance configurations at zero installation angle. The flow on the single wheel and on the front wheel of the tandem wheels is affected by laminar-turbulent transitional features. The vortical structures past the tandem wheels consist of four vortices that detach from the tyre shoulders of the front wheel and interact with the rear wheel. The study and obtained databases contribute to the general understanding of the complex flow and help to improve engineering predication of the gear aerodynamic loads.

1. Introduction

Most of the existing research on the flow past landing gears focuses on aeroacoustics because of the increasingly stringent noise requirements and due to the fact that landing gears are still one of the main sources of noise of civil aircraft (Dobrzynski, 2010) during the approach and landing phases. Obtaining a good understanding of the unsteady flow features is not only useful in order to predict noise, but also to correctly estimate the mean and unsteady aerodynamic forces.

For a rudimentary four-wheel landing gear, mean lift, drag and side forces were measured by Venkatakrishnan et al. (2012). It was found that the strut strongly affects the flow field around the two in-line wheels. Lazos (2002) measured the flow velocity in a streamwise plane surrounding the wheels of a four-wheel undercarriage by particle image velocimetry (PIV). The measurement identified different flow states at low frequency. Stalnov et al. (2013) experimentally studied a simplified quarter-scale model of a main landing gear. In addition to aeroacoustic measurements, mean aerodynamic loads were measured sequentially on sub-

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Nomenclature

C_D	Drag coefficient (x-axis), $C_D = F_x/(\rho S U_\infty^2/2)$	x, y, z	Global coordinate system, m
C_L	Lift coefficient (y-axis), $C_L = F_y/(\rho S U_\infty^2/2)$	z_c	Confidence coefficient
C_p	Pressure coefficient $C_p = (p - p_\infty)/(\rho U_\infty^2/2)$	∞	Free-stream value
D_w	Wheel diameter, m	p	PIV axis
F	Force vector, N	RMS	Root Mean Square
k	Turbulent kinetic energy (2D): $k = (\overline{(u'_x)^2} + \overline{(u'_y)^2})/2$, m²/s²	α	Installation angle, deg
L_w	Inter-axis distance, m	ϵ_μ	Relative error on the mean
N	Number of PIV frames	ϵ_σ	Relative error on the standard deviation
p	Pressure, Pa	ν	Kinematic viscosity of air, m²/s
R	Wheel-shoulder radius, m	ρ	Density of air, kg/m³
Re_D	Reynolds number	θ	Wheel azimuthal angle, deg
S	Frontal projected wheel area $S = 0.01285$ m²	$'$	Fluctuating part
St	Strouhal number	$\bar{\cdot}$	Time average
T	Transfer function	f	Front wheel
U	Velocity, m/s	r	Rear wheel
		t	Total

assemblies of the landing gear, from an isolated main strut to a full assembly, mounting the components sequentially. In this way it was possible to analyse the effect of the various components on the landing-gear aerodynamic loads and noise, but it was not possible to isolate the effects of the interactions between wheels and struts. The model was studied for multiple installation angles of the bogie. Other works on aircraft undercarriages were performed on the Boeing 777 main landing gear (Humphreys and Brooks, 2007), on the Gulfstream G550 nose landing gear (Zawodny et al., 2009), and on the Airbus LAGOON nose landing gear (Manoha et al., 2008). However, unsteady aerodynamic loads were not quantified experimentally in any of these studies.

In contrast to the studies described above, in which complex assemblies are considered, there are a number of studies on elementary geometries, representing parts of a landing gear. These studies are generally meant to provide a better understanding of the flow features. For instance the work by Khorrami et al. (2007) provided experimental data on tandem cylinders (Sumner, 2010; Okajima, 1979). On the same tandem-cylinders geometry, Xiao and Luo (2013) tested the Improved Delayed Detached-Eddy simulations (IDDES) by Shur et al. (2008). A dedicated tandem-cylinder benchmark case was extensively tested in the NASA low-speed aeroacoustic wind tunnel to provide a database for aeroacoustic predictions (Lockard, 2011), followed by simulations on the same geometry.

The flow past isolated wheels is similar to the flow past small-aspect-ratio cylinders. Zdravkovich et al. (1998) experimentally studied the flow past small-aspect-ratio cylinders with two free ends in the critical regime $2 \times 10^5 < Re < 6 \times 10^5$. It was found that the wake is dominated by a vortex system that is formed by four vortex filaments. Similar flow features were noticed on more realistic wheel shapes too. McManus and Zhang (2005) performed simulations on the flow past an isolated wheel in contact with both stationary and moving ground at a Reynolds number of 5.3×10^6. When the wheel is stationary on the ground, two opposite vortices form on the top wheel shoulders. On the contrary, when the wheel is rotating, the separated flow on the top part of the wheel forms an arch vortex layer. Later, Zhang et al. (2013) experimentally studied the flow past the 1/3-scale CADWIE isolated wheel with two different hubs that did not have any significant effect on the flow.

For the purpose of measuring both mean and unsteady aerodynamic loads, strain-gauge balances are commonly used (Tropea et al., 2003). The strain is measured on the sensor structure and, after calibration, the forces are estimated. For example, unsteady data for wind aerodynamic loads on wind-turbine models were obtained with a strain-gauge based balance by Hu et al. (2012), where the balance was able to capture the unsteady loads at the blade rotation speed and at the higher harmonic frequencies up to three times the rotation speed. In the literature, attempts with direct application of strain gauges to some relevant points of the models exist. For example, Schuster and Byrd (2003) applied strain gauges but only the data from the pressure sensors were considered reliable due to the influence of the structural dynamic modes on the strain gauges. For short-duration force measurements (e.g., Robinson and Hannemann, 2006), models and special calibration rigs have to be prepared. This is more complex than the previous case because the model is designed for the purpose of the dynamic calibration.

Another approach is to obtain the loads by integrating the measured surface pressure using pressure sensitive paint (De Lucca et al., 2013) and piezoelectric sensors for high frequency local information for both surface shear stress and surface pressure (Nitsche and Mirow, 1989; Baban et al., 1989; Capece and Fleeter, 1986). In some specific cases, more complex techniques can be applied. For example, on two-dimensional geometries, time-resolved PIV can be used to estimate the forces on the model (Kurtulus et al., 2007), whilst small-size models can be supported by a magnetic suspension system (Sawanda and Suda, 2011) that measures the forces.

Concerning the analysis of the flow features, Proper Orthogonal Decomposition (POD) has been used to extract the modes of the flow field, both in experiments and simulations. Examples are Meyer et al. (2007), comparing PIV data with Large Eddy Simulations (LES), Bernero and Fiedler (2000) on PIV data, and Tirunagari et al. (2012) on LES data. There is the need of using such a technique because the turbulent flow in the wake is chaotic and random, and POD allows the identification of the coherent structures and their classification by energy content (Berkooz et al., 1993).