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CFD analysis of dynamic stall on vertical axis wind turbines using Scale-Adaptive Simulation (SAS): Comparison against URANS and hybrid RANS/LES

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ABSTRACT

The Scale-Adaptive Simulation (SAS) approach has emerged as an improved unsteady Reynolds-Averaged Navier-Stokes (URANS) formulation to bridge the gap between the less accurate commonly used URANS and the computationally expensive hybrid RANS/LES for highly separated unsteady flows, e.g. dynamic stall. However, while the SAS has been successfully used at several occasions, it has not yet been tested for the complex case of dynamic stall. Therefore, the present study analyzes the SAS predictions of dynamic stall on a vertical axis wind turbine at a chord Reynolds number of 5×10^4 and a reduced frequency of 0.125. The analysis is based on comparison of the SAS predictions of the blade aerodynamics and the turbine power performance against the corresponding URANS and hybrid RANS/LES predictions. The results show that the SAS predictions are closer to hybrid RANS/LES than URANS with respect to: (i) the instant of the bursting of the laminar separation bubble (LSB), the leading-edge suction collapse, the formation of the dynamic stall vortex (DSV) and the trailing-edge vortex (TEV) and the shedding of the TEV; (ii) the size and strength of the TEV; (iii) the DSV-TEV interaction; (iv) the drag prediction during the downstroke. On the other hand, both URANS and SAS fail to corroborate with hybrid RANS/LES with respect to: (i) the instant of the formation of the LSB and the shedding of the DSV (the stall angle); (ii) the drag jump at the stall angle; (iii) the lift values during the downstroke; and (iv) the chordwise extent of the LSB.

1. Introduction

Dynamic stall on an airfoil is a very complex unsteady fluid dynamics problem that occurs due to large excursions of the angle of attack α , beyond the static stall angle α_{ss} . The rich flow physics of the dynamic stall phenomenon, as documented in the literature [1–10], can be characterized by (i) a noticeable delay in separation compared to the static case; (ii) formation of a large-scale dynamic stall vortex (DSV); (iii) a delayed stall angle and elevated aerodynamic loads prior to stall compared to the static case; and (iv) a sudden drop in aerodynamic loads, by shedding of the DSV, followed by massive fluctuations in aerodynamic loads. These load fluctuations can result in structural vibrations and, thus, reduce the system life due to fatigue. In addition, considerable noise can be generated, the global aerodynamic performance of the system can be largely deteriorated, and if present, the drivetrain/gearbox can be damaged [11–18].

Dynamic stall is of high relevance to several applications, such as

helicopters [19–24], airplanes [11,12,25], micro-air vehicles [25,26], flapping wings [13,27], horizontal axis wind turbines (HAWTs) [28–37] and vertical axis wind turbines (VAWTs) [15,38–51]. It should be noted that in the vast majority of these applications, dynamic stall occurs in a non-oscillating inflow condition. Dynamic stall on VAWTs at low tip speed ratios, however, is highly sophisticated because during a turbine half-revolution while the turbine blade experiences the dynamic stall (due to large excursions of α), simultaneously the relative velocity V_{rel} experienced by the blade is also considerably varying. Fig. 1 illustrates a schematic of simultaneous variations of angle of attack and relative velocity for a VAWT operating in dynamic stall at low tip speed ratios. The simultaneous variations of α and V_{rel} impose two sources of flow unsteadiness where their impacts on the boundary layer events and the separation onset are dissimilar. The excursions of α , at a given inflow, are known to reform the shape and magnitude of the pressure gradient along the surface while the variations of V_{rel} , for a fixed surface, only modify the magnitude of the pressure gradient along

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Nomenclature

A	Turbine swept area, $h \cdot d$ [m^2]
c	Blade chord length [m]
C_d	Sectional drag coefficient, $D/(0.5\rho c V_{rel}^2)$ [-]
C_f	Skin friction coefficient [-]
C_{Fn}	Turbine normal force coefficient [-]
C_{Ft}	Turbine tangential force coefficient [-]
C_l	Sectional lift coefficient, $L/(0.5\rho c V_{rel}^2)$ [-]
C_m	Instantaneous moment coefficient [-]
C_P	Power coefficient, $P/(qAU_\infty)$ [-]
C_T	Thrust coefficient, $T/(qA)$ [-]
CoP	Pressure coefficient [-]
d	Turbine diameter [m]
dz	Spanwise grid resolution [m]
D	Sectional drag force [N/m]
f_s	Shielding function
h	Turbine height [m]
k	Turbulent kinetic energy [m^2/s^2]
K	Reduced frequency, $\Omega c/(2V_{rel}) \approx c/2R$ [-]
l	Turbulence integral length scale [m]
L	Sectional lift force [N/m]
M	Turbine moment [Nm]
n	Number of blades [-]
P	Turbine power [W]
q	Dynamic pressure [Pa]
R	Turbine radius [m]
Re_c	Chord-based Reynolds number, $cU_\infty\sqrt{1+\lambda^2}/\nu$ [-]
Re_θ	Momentum-thickness Reynolds number [-]
t	Time [s]
T	Turbine thrust force [N]
TI	Approach-flow (i.e. inlet) total turbulence intensity [%]
TI_i	Incident-flow total turbulence intensity [%]
u_*	Friction velocity [m/s]
U_∞	Freestream velocity [m/s]
V	Velocity magnitude [m/s]
V_{rel}	Experienced relative instantaneous velocity [m/s]

$V_{rel,n}$	Experienced relative instantaneous velocity normalized with $U_\infty\sqrt{1+\lambda^2}$ [-]
X	Chordwise distance along the blade [m]
ΔX^+	Chordwise dimensionless spacing along the blade, $u_*\Delta X/\nu$ [-]
Y_p	Wall-normal distance of the first cell center [m]
Y^+	Wall-normal dimensionless spacing along the blade, u_*Y_p/ν [-]
Z	Spanwise distance along the blade [m]
ΔZ^+	Spanwise dimensionless spacing along the blade, $u_*\Delta Z/\nu$ [-]
α	Experienced angle of attack [$^\circ$]
α_{ss}	Static stall angle [$^\circ$]
γ	Intermittency [-]
ε	Turbulence dissipation rate [m^2/s^3]
θ	Azimuth angle [$^\circ$]
λ	Tip speed ratio, $R\Omega/U_\infty$ [-]
μ_t	Eddy (turbulent) viscosity [Pa.s]
ν	Kinematic viscosity of air [m^2/s]
σ	Solidity, [-]
τ	Shear stress [Pa]
ω	Specific dissipation rate [1/s]
Ω	Turbine rotational speed [rad/s]
DSV	Dynamic stall vortex
GCI	Grid convergence index
HRL	Hybrid RANS/LES
LE	Leading edge
LES	Large Eddy Simulation
LSB	Laminar separation bubble
SAS	Scale-Adaptive Simulation
$SBES$	Stress-Blended Eddy Simulation
SRS	Scale-Resolving Simulation
SV	Secondary vortex
TE	Trailing edge
TEV	Trailing-edge vortex
$URANS$	Unsteady Reynolds-Averaged Navier Stokes

the surface leaving the shape unchanged [52]. For a given inflow, increasing α during the blade upstroke resembles a downstream-moving wall where the boundary layer has a fuller velocity profile and is more resistant to separation, therefore, the separation on the surface is delayed compared to the static case [52]. Conversely, decreasing α during the blade downstroke resembles an upstream-moving wall where the velocity profile is less full, thus, the separation is promoted due to

higher susceptibility of the boundary layer to separation [9,10,52]. On the other hand, for a fixed surface with adverse pressure gradient, unsteady oscillating inflow is known to simply promote boundary layer separation [53,54]. Therefore, the combined impact of simultaneous oscillations of α and V_{rel} on the unsteady flow separation on the surface further complicates the blade aerodynamics of VAWTs.

Computational fluid dynamics (CFD) has been widely employed to investigate the complex dynamic stall phenomenon for different applications, including VAWTs [8,55–57]. In the vast majority of these studies the unsteady Reynolds-Averaged Navier-Stokes (URANS) approach has been used. The URANS can identify the global features of the dynamic stall such as the formation of the large coherent structure dynamic stall vortex (DSV). However, as highlighted by Spalart [58], Reynolds-averaged turbulence modeling is not capable of accurately predicting the boundary layer growth and separation onset, and the post-separation momentum transfer, which are the essential features of the dynamic stall phenomenon. Therefore, the accurate prediction of the dynamic stall using URANS is a highly challenging task [58,59].

In this perspective, more advanced scale-resolving turbulence modeling approaches, such as the classic wall-resolved large eddy simulation (LES), wall-modeled LES and hybrid RANS/LES models, which partially resolve the turbulence spectrum, can more accurately account for the impact of the turbulence on the separation onset and growth and therefore could be viable solutions for predicting dynamic stall. A limited number of studies have employed scale-resolving simulations to analyze the flow physics of dynamic stall for pitching/

Fig. 1. Illustration of simultaneous variations of angle of attack and relative velocity for a VAWT blade at low tip speed ratios.

plunging plates/airfoils, e.g. Visbal et al. [11,12,25,60], Garmann et al. [61] and Kim and Xie [29]. However, the extremely high computational cost of scale-resolving simulations [62] is highly prohibitive to employ the approach for engineering applications at high Reynolds numbers such as wind turbines [63].

To bridge this gap between the less accurate and commonly used URANS and the high accuracy but computationally expensive scale-resolving simulations, the Scale-Adaptive Simulation (SAS) approach has been provided by Menter and Egorov and Egorov et al. [64,65]. This approach is basically an improved URANS formulation which can use any of the existing Reynolds-averaged turbulence models while allowing for the turbulence structures to be (partially) resolved for highly separated and unsteady flows based on the von Karman length scale filter [65–68]. The von Karman length scale filter is selected to eliminate the explicit influence of the grid spacing on the switch between the RANS and LES, which is present for the most popular hybrid RANS/LES approach, i.e. Detached Eddy Simulation (DES) [69]. SAS, although it behaves similar to DES for detached flows, is generally a more conservative choice, because the switch from RANS to LES is avoided where the spatial or temporal resolution of the simulation is insufficient for LES. Therefore, SAS is more suitable for complex engineering applications where the computational grid might not be prepared strictly according to the LES grid requirements [62,65].

SAS has been tested for several applications, such as combustion chambers, gas turbine blades, chemical mixers, car mirrors and internal combustion engines [65]. However, to the best of our knowledge, it has not yet been evaluated for the complex case of dynamic stall. Therefore, this paper intends to analyze the predictions of SAS for the case of dynamic stall on a VAWT blade undergoing simultaneous large excursions of angle of attack and relative velocity. The analysis is based on a detailed comparison of the SAS results with the corresponding 2.5D URANS and hybrid RANS/LES results. A detailed comparative analysis of the blade aerodynamics (in terms of the lift and drag load coefficients on the blade, surface pressure and skin friction coefficients along the blade suction side, the vorticity field around the blade) and the turbine power performance (in terms of the instantaneous tangential and normal load coefficients) is performed. The findings will be of high significance to support further improvement of more accurate yet computationally affordable turbulence modeling approaches for CFD simulations of dynamic stall.

The outline of the paper is as follows: Section 2 describes the numerical approaches. The computational settings and parameters are mentioned in Section 3. Section 4 presents the solution verification and validation studies. The results for the blade aerodynamics and the turbine aerodynamic performance are presented in Section 5. Discussion and conclusions are provided in Section 6 and 7.

2. URANS, SAS and hybrid RANS/LES

In the present study, three different approaches are employed for the aerodynamic analysis of the turbine operating in dynamic stall: unsteady Reynolds-Averaged Navier-Stokes (URANS), hybrid RANS/LES simulation and Scale-Adaptive Simulation (SAS).

- 2.5D URANS

URANS simulations are employed as they are much less computationally expensive than scale-resolving simulations due to less strict spatial and temporal requirements for the computational settings. The comparatively low computational cost enables extensive parametric studies to characterize and improve the aerodynamic performance of wind turbines. The URANS formulation is derived from the

instantaneous Navier-Stokes equations using the Reynolds decomposition and ensemble averaging. The appearance of the nonlinear Reynolds stress terms in the URANS equations necessitates the use of so-called turbulence modeling equations for the closure problem [70]. Therefore, for transitional and turbulent flows, URANS is considered to be less accurate than the scale-resolving simulations simply because the impact of the turbulence is modeled rather than resolved.

- 2.5D Hybrid RANS/LES: reference case

As a more advanced scale-resolving simulation approach, hybrid RANS/LES is used. The employed hybrid RANS/LES approach is Stress-Blended Eddy Simulation (SBES) [71]. SBES is designed to overcome the major weaknesses of the DES approaches (i.e. DES, DDES and IDDES [69]), namely grid-induced separation (GIS), slow transition from RANS to LES in separating shear layer, and unclear distinction between the RANS and LES regions [71]. SBES is basically an automatic zonal modeling approach capable of blending the existing RANS and LES approaches on the stress level via an advanced blending function, see Eq. (1) [71], where τ_{ij} and f_s are shear stress and shielding function, respectively. For eddy-viscosity models, the equation reduces to Eq. (2) [71], where μ_t is the eddy viscosity. The blending of the RANS and LES solutions is designed to provide an asymptotic shielding of the attached RANS boundary layer, which therefore prevents the grid-induced separation [71]. It can be seen that the complexity of the approach lies in delicate design of the shielding function f_s to perfectly shield the boundary layer in RANS while yielding a swift shift to LES where applicable. The high capabilities of SBES make it one of the most promising hybrid RANS/LES approaches available [71]. SBES can be coupled with any of the existing RANS and LES models.

$$\tau_{ij} = \tau_{ij}^{RANS} f_s + \tau_{ij}^{LES} (1 - f_s) \quad (1)$$

$$\mu_t = \mu_t^{RANS} f_s + \mu_t^{LES} (1 - f_s) \quad (2)$$

- 2.5D SAS

As an intermediate approach between the less accurate commonly used URANS and the high accuracy but computationally expensive hybrid RANS/LES approach, the SAS approach [64,65] is employed. SAS is based on improving the k - kl model by Rotta [72] via introducing an improved length-scale equation for $k\sqrt{l}$, where k is the turbulent kinetic energy and l is the integral length scale of turbulence. SAS is basically an improved URANS formulation allowing for the turbulence structures to be (partially) resolved for highly separated and unsteady flows. Therefore, the approach is capable of producing spectral content for unsteady separated flows. The approach employs the von Karman length scale filter, rather than the typical filter defined using the grid spacing in DES [69], to switch between RANS and LES [65–68]. The elimination of the explicit dependence of the filter on grid spacing allows SAS, although behaving similar to DES for detached flows, to be generally a more conservative choice, because the switch from RANS to LES is avoided where the spatial or temporal resolution of the simulation is insufficient for LES. Therefore, it is more suitable for complex engineering applications where the computational grid might/could not be prepared strictly according to the LES grid requirements [62,65]. The SAS approach can be formulated using any of the existing Reynolds-averaged turbulence models.

Fig. 2. Schematic of the turbine. The (-) and (+) signs denote the suction and pressure sides during the half-revolution, $0^\circ \leq \theta < 180^\circ$, respectively.

3. Computational settings and parameters

3.1. Turbine characteristics

The turbine is a one-bladed, clockwise-rotating, straight-bladed H-type vertical-axis wind turbine schematically depicted in Fig. 2. A single blade-spoke connection is located at the quarter-chord. To reduce the computational cost, the turbine shaft and the spoke are not taken into account. Note that since the focus of the present study is on the first half of the turbine revolution, the shaft and spoke have negligible effect on the flow topology [73]. The geometrical and operational characteristics of the turbine are presented in Table 1.

3.2. Computational settings

- 2.5D URANS

The 2.5D computational domain has dimensions $20d \times 20d \times 0.5c$ (Fig. 3), where 'd' and 'c' are turbine diameter and blade chord length, respectively. The distance from the turbine center to the domain inlet and outlet are $10d$. The blockage ratio is 5%. The domain consists of a rotating core, with a diameter of $1.5d$, to facilitate the turbine rotation and a surrounding fixed domain. The size of computational domain in top-view, see Fig. 3, is based on the guidelines in Ref. [74,75]. The domain spanwise size is half-chord, $0.5c$, which is selected based on the sensitivity analysis presented later in this section.

The computational grid consists of 4,782,010 quadrilateral cells. The maximum and average y^+ values are about 1 and 0.3, respectively. The number of cells along the blade cross-section circumference is 800. The number of cells along the domain span is 30, corresponding to a spanwise grid resolution of $\frac{dz}{c} = \frac{1}{60}$. A grid sensitivity analysis is also performed. Further information about this analysis and the results will be presented later in this section.

Table 1

Geometrical and operational characteristics of the turbine.

Parameter	Value	Parameter	Value
Number of blades, n	1	Freestream velocity, U_∞ [m/s]	7.5
Diameter, d [m]	0.4	Turbine rotational velocity, Ω [rad/s]	75
Height, h [m]	1	Inlet total turbulence intensity, TI [%]	5
Airfoil chord, c [m]	0.05	Inlet turbulence length scale [m]	0.4
Solidity, σ	0.125	Tip speed ratio, λ	2
Blade aspect ratio, h/c	20	Chord Reynolds number, Re_c	5×10^4
Airfoil	NACA0015	Reduced frequency, K	0.125

The boundary conditions are: (i) uniform mean velocity inlet, (ii) zero static gauge pressure outlet, (iii) symmetry sides, (iv) no-slip airfoil walls, and (v) periodic spanwise sides. The approach-flow (i.e. inlet) total turbulence intensity is 5%. Note that the incident-flow total turbulence intensity is 3.96% representing the real value experienced by the turbine calculated using an empty domain [75–78]. The inlet turbulence length scale is considered to be equal to the turbine diameter, 0.4 m.

Turbulence is modeled using the four-equation γ - Re_θ model [79,80], also known as the Transition SST (TSST) model. The TSST model solves two additional transport equations, one for the intermittency γ and one for the momentum-thickness Reynolds number Re_θ , together with the two transport equations of the SST k - ω model to account for the laminar-to-turbulent transition. The production limiters by Menter [81] and Kato and Launder [82] are employed to limit the turbulence production in the stagnation regions. The TSST turbulence model is selected based on a previous detailed comparison of the predictions of URANS simulations of VAWTs using different turbulence models [83].

The incompressible simulations are performed using the commercial CFD software ANSYS Fluent 16.1 with the SIMPLE scheme for pressure-velocity coupling [84] and second-order temporal and spatial discretization. The incompressibility assumption for air is made because the experienced velocity by the blade is predicted to be < 20 m/s, corresponding to a Mach number (flow velocity/local sound speed) of < 0.06 , where the compressibility effects are negligible [85]. The azimuthal increment $d\theta$ is 0.1° , with 20 iterations per time step. 20 turbine revolutions are performed to reach statistical convergence. The presented results are sampled at the 21st turbine revolution. The employed azimuthal increment and the convergence criterion are based on the guidelines in Ref. [74,75].

- 2.5D hybrid RANS/LES: reference case

The computational domain has dimensions $20d \times 20d \times 0.25c$, where the 2D cross-section is the same as for the URANS simulations. The spanwise domain size for the scale-resolving simulations is a quarter-chord, which is in line with typically selected spanwise domain size for the scale-resolving simulations of airfoils at high angles of attack at similar operating conditions [11,86–89].

The computational grid consists of 37,417,411 quadrilateral cells where the grid is generated based on the best-practice guidelines for scale-resolving simulations [87,90]. The maximum and average y^+ values are about 1 and 0.3, respectively. The maximum Δx^+ value is 20, with an average value of 6. The maximum and average Δz^+ values are approximately the same as the Δx^+ values. The wall-unit spacing values are in line with the recommended standard grid resolution for scale-resolving simulation of airfoils [86–88,91].

Similar boundary conditions as for the URANS simulations are employed. At the domain inlet, the vortex method [92] with 438 vortices is employed to generate the turbulence. The number of vortices corresponds to a quarter of the number of cell faces at the domain inlet

Fig. 3. Top view of the computational domain.

and is selected based on the best-practice guidelines in Ref. [93]. In the present study, SBES employs the Wall-Adapting Local Eddy-Viscosity (WALE) subgrid-scale model [94] in the LES region. In the RANS region, it employs the three-equation SSTI model, i.e. SST $k-\omega$ model with one additional transport equation for the intermittency γ [93,95]. The combination is termed ‘SSTI-SBES’. Production limiters by Menter [81] and Kato and Launder [82] are also employed to limit the turbulence production in the stagnation areas in the RANS region.

The bounded central-differencing discretization for the momentum equations and the bounded second-order implicit transient formulation

are employed. The azimuthal increment is 0.01° , with 2 iterations per time step, to ensure the maximum CFL < 1 in the whole domain. The rest of the computational settings are the same as those for the URANS simulations.

The simulation procedure is as follows: the 2.5D SBES simulation is initialized with the solution of the 2.5D URANS after 20 turbine revolutions. The SBES simulation is then continued for another 5 turbine revolutions to ensure sufficient development of the turbulent structures throughout the domain. The results are sampled at the 6th turbine revolution.

- 2.5D SAS

The computational domain size for SAS is the same as for the hybrid RANS/LES simulations, i.e. $20d \times 20d \times 0.25c$. With respect to the intention for the employment of the SAS approach, i.e. to represent an intermediate approach between the less accurate commonly used URANS and the high accuracy but computationally expensive hybrid RANS/LES approach, the computational grid for the SAS simulations is generated with a total of 19,753,402 quadrilateral cells (see Fig. 4). The maximum and average y^+ values are about 1 and 0.3, respectively. The maximum ΔX^+ (chordwise wall-unit spacing along the blade) value is 26, with an average value of 9. The maximum and average ΔZ^+ (spanwise wall-unit spacing along the blade) values are approximately the same as the ΔX^+ values. The wall-unit spacing values are in line with the recommended standard grid resolution for scale-resolving simulation of airfoils [87].

Similar boundary conditions and computational settings as for the hybrid RANS/LES simulations are employed. At the domain inlet, the vortex method [92] with 251 vortices is employed to generate the

Fig. 4. Computational grid of the turbine for the SAS simulation with a total of 19,753,402 quadrilateral cells.

Fig. 5. Turbine tangential and normal force coefficients for domains with different spanwise size.

turbulence. The number of vortices corresponds to a quarter of the number of cell faces at the domain inlet and is selected based on the best-practice guidelines in Ref. [93]. In the present study, the SAS approach is formulated using the four-equation transition SST model [79] and the combination is termed ‘TSST-SAS’.

The simulation procedure is as follows: the SAS simulation is initialized with the solution of the 2.5D URANS after 20 turbine revolutions. The SAS simulation is then continued for another 5 turbine revolutions to ensure sufficient development of the turbulent structures throughout the domain. The results are sampled at the 6th turbine revolution.

4. Solution verification and validation

- 2.5D URANS

A sensitivity analysis is performed to study the impact of the spanwise size of the computational domain. Fig. 5 shows the comparison of the turbine tangential and normal load coefficients calculated using domains with different spanwise size, i.e. 0 (2D), 0.25c and 0.5c. A negligible difference in thrust coefficient C_T ($\approx 2\%$) between the domains with the different spanwise size is observed.

The grid convergence analysis is performed using three grids

uniformly refined with a linear refinement factor of $\sqrt{2}$. Fig. 6a and b depict the turbine tangential and normal load coefficients for the three grids. The Grid Convergence Index (GCI) by Roache [96] is employed to quantify the results of the grid convergence study. For the medium-fine grid pair, the GCI values calculated using C_T with a safety factor of 1.25 are $GCI^{\text{coarse}} = 0.0057$ (1.33% of the exact value of C_T calculated using the Richardson extrapolation method) and $GCI^{\text{fine}} = 0.0032$ (0.75% of the exact value of C_T calculated using the Richardson extrapolation method). Note that for the GCI calculations for wind turbines, it is typical to employ the turbine power coefficient C_p (i.e. the integral of the C_{Ft} values shown in Fig. 6a), e.g. see Ref. [74,75]. However, in the present study because the turbine is operating in dynamic stall and the C_p values are very low and close to zero, therefore, C_p cannot be employed for the GCI calculations. Instead, the second key power performance parameter for the turbine, namely the turbine thrust coefficient C_T , is employed to calculate the presented GCI values.

In addition, a sensitivity analysis is performed to study the impact of the grid resolution in the spanwise direction where the results calculated using the medium grid with three different spanwise grid resolutions of $\frac{dz}{c} = \frac{1}{40}$, $\frac{1}{60}$ and $\frac{1}{100}$ are compared, see Fig. 6c and d. The comparison of the turbine tangential and normal load coefficients reveals that the three lines are almost overlapping. In the present study, the medium grid with 30 cells in the spanwise direction, $\frac{dz}{c} = \frac{1}{60}$, is employed.

Three validation studies have been performed for three VAWTs with different geometrical and operational characteristics where the focus is on the turbine power performance, mean velocity in the turbine wake and the turbine blade aerodynamics.

In the first validation study, the power performance, C_p , of a three-bladed turbine is compared with the experimental data by Castelli et al. [97]. The experimental data are based on the low-frequency torque measurement at the low-turbulence wind tunnel at Politecnico di Milano. The turbine has a solidity of 0.25 and the blades are symmetric NACA0021 airfoils. The turbine operates at tip speed ratios of 2.04–3.08, the chord Reynolds numbers are 0.91×10^5 – 1.8×10^5 and the reduced frequency is 0.082. The results are shown in Fig. 7a and Table 2. The absolute deviation between the CFD and the experimental results is 0.5–23.2%.

In the second validation study, the mean streamwise and lateral velocity components in the turbine wake at several downstream locations are compared with the experimental data by Tescione et al. [98]. The experimental data are based on particle image velocimetry (PIV) measurements in the open jet facility at TU Delft. The turbine has a solidity of 0.12 and the blades are symmetric NACA0018 airfoils. The turbine operates at a tip speed ratio of 4.5, the chord Reynolds number is 1.7×10^5 and the reduced frequency is 0.06. The results are presented in Fig. 7b and Table 2. The absolute deviation between the CFD and the experimental results at $x/R = 2.0$ in the turbine near wake, averaged over the lateral direction, is 6.8–12.3% and 2.2–2.8% for the streamwise and lateral components, respectively.

In the third validation study, the DSV evolution within the rotor plane and the strength of the circulation of the DSV are compared with the experimental data by Ferreira et al. [15]. The experimental data are based on the PIV measurement at the low-turbulence wind tunnel at TU Delft. The turbine has a solidity of 0.125 and the blades are symmetric NACA0015 airfoils. The turbine operates at a tip speed ratio of 2.0, the chord Reynolds numbers is 0.5×10^5 and the reduced frequency is 0.125. Fig. 7c and Table 2 show the comparison between the CFD and the experimental results. It can be seen that the deviation is between 4.5% and 31.1%, which for the majority of the azimuthal positions is within the experimental uncertainty.

Some possible explanations for the observed deviations between the

Fig. 6. (a) Tangential and (b) normal force coefficients for three uniformly refined grids. (c–d) Same for grids with different spanwise resolution.

presented CFD results and the experimental data, which are common for the three validations, are firstly the geometrical simplifications made in the CFD modeling due to neglecting the turbine structural components; secondly the limitations of the 2D URANS; and thirdly the differences in data (phase/time-) averaging between CFD and the experiments. Further explanations for each of the validations are extensively presented in Ref. [75,83,99–101], which for brevity are not repeated here.

- 2.5D Hybrid RANS/LES: reference case

The three validation studies presented for URANS have been performed using the TSST turbulence model. The SSTI model is a successor of the TSST model and is already found to provide reasonable agreement with the experimental data and comparable predictions with the TSST model for the flow around VAWTs [73,83]. Therefore, employing the SSTI model in the RANS region of the SBES simulation ensures the accuracy of the predictions in this region. The SBES itself has been extensively validated by Menter [71] in comparison against experiments for several test cases, e.g. diffuser, flat plate and periodic channel flow.

- 2.5D SAS

The three validation studies presented for URANS have been performed using the TSST turbulence model. Note that the validated turbulence model is also employed in the RANS region of the SAS approach to ensure the accuracy of the predictions in this region. SAS itself has been extensively validated by Egorov et al. [65], Duda et al. [102] and Menter and Egorov [103] against different experimental sets for flow applications including stalled airfoil and full aircraft.

5. Results

As already mentioned, SBES is one of the most advanced hybrid RANS/LES approaches providing optimal shielding of the attached boundary layer with RANS (i.e. the inclusion of the attached boundary layer in the LES region is strongly avoided) and a smooth blending from RANS to LES. Therefore, in the present study, SBES is employed as the reference to analyze the effectiveness of the SAS in realizing the promise of bridging the gap between the URANS and the hybrid RANS/LES. This is made by comparison of the SAS and the URANS results against the reference case to identify in what aspects the SAS predictions are closer to the reference case than the URANS.

Fig. 7. Three sets of validations for URANS simulations: (a) turbine power coefficient compared with Ref. [97]; (b) normalized mean streamwise velocity along the lateral direction at $x/R = 2.0$ downstream in turbine wake at $\lambda = 4.5$ compared with Ref. [98]; and (c) normalized strength of the circulation of separated/shed leading-edge (clockwise) vortex at $\lambda = 2.0$ compared with Ref. [15]. The CFD results are calculated over the last turbine revolution.

5.1. Blade aerodynamics

Fig. 8 shows the variations of α and V_{rel} experienced by the blade, as the two sources of aerodynamic unsteadiness for VAWTs, based on the URANS, the SAS and the SBES (reference) predictions. It can be seen that the three lines are almost overlapping implying that the time-averaged kinematics and operating conditions that the blade

experiences predicted by three approaches are the same. Therefore, any differences in the predicted aerodynamics, loads and turbine power performance are not directly due to the non-identical experienced α and V_{rel} but rather due to the different predictions of the boundary layer events at the same α and V_{rel} . Note that the α and V_{rel} values are directly calculated from the CFD results using the method described in Ref. [100]. Also note that due to the turbine blockage, when the flow reaches the turbine it is deflected to the sides (i.e. streamtube expansion). This causes a small negative α at $\theta = 0^\circ$ and 180° .

Figs. 9 and 10 present the instantaneous spatiotemporal contours of instantaneous surface pressure and skin friction coefficients along the blade suction side (inner side: see Fig. 2) at mid-span during the turbine half-revolution. Fig. 11 illustrates the histories of instantaneous surface pressure coefficient at selected chordwise positions, $X/c = 0.01, 0.025, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7$ and 0.8 , along the blade suction side at mid-span.

The laminar separation bubble (LSB) can be recognized by a strong suction imprint on the surface pressure contour plot along the blade (see Fig. 9). Regarding the LSB, the following points are noted:

- Formation of the LSB:** The SAS and the URANS predictions of the instant of the LSB formation are in line with that of the reference case.
- Chordwise extent of the LSB:** SAS and URANS predict slightly smaller LSB size compared to the reference case. For instance at $\theta = 58^\circ$, the chordwise extent of the LSB predicted by SAS, URANS and SBES (reference) are 6.7%, 7.7% and 8.7%, respectively.
- Bursting of LSB and the follow-up leading-edge suction collapse:** Both SAS and URANS predict an earlier bursting of the LSB and the follow-up leading-edge suction collapse, compared to the reference case, where the difference is more significant for URANS.

Therefore, SAS provides closer predictions to the reference case than URANS with respect to the instant of the LSB shedding and the leading-edge suction collapse.

The dynamic stall vortex (DSV), which is formed by the LSB bursting and then grows in size while traveling downstream along the blade chord, is recognized by a suction imprint on the surface pressure spatiotemporal contour plot, where such imprint stretches diagonally from the LSB towards the trailing edge (see Fig. 9). The DSV can also be recognized by the footpath of the reverse flow with resultant negative skin friction coefficient (see Fig. 10). Regarding the DSV, the following points are notable:

- Formation of the DSV:** As both SAS and URANS predict an earlier bursting of the LSB, compared to the reference case, they also predict an earlier formation of the DSV. This is more significant for URANS.
- Traveling of the DSV:** Monitoring the histories of the surface pressure along the blade at selected chordwise positions (see Fig. 11) shows that the SAS-predicted DSV arrives at each chordwise position earlier, i.e. at smaller θ , than the reference case predictions. This is consistent with the fact that SAS predicts an earlier formation of the DSV than the reference case. Such early prediction is even more significant for URANS.
- Shedding of the DSV:** Both SAS and URANS predict a significantly earlier shedding of the DSV compared to the reference case. This is more prominent for SAS.
- Secondary/tertiary vortices:** After the shedding of the DSV, URANS predicts the formation, growth and shedding of secondary and tertiary vortices. SAS shows a similar prediction of a secondary, but no tertiary, vortex. These predictions are not supported by the reference case where no secondary/tertiary vortex is shed.

The turbulent trailing-edge vortex (TEV), which is rolled up from the blade pressure side, is formed just by the shedding of the DSV. The

Table 2

Three sets of validations: comparison of CFD with the experiments by Castelli et al. [97], Tescione et al. [98], and Ferreira et al. [15].

Validation study 1					
λ	2.04	2.33	2.51	2.64	3.08
Absolute deviation of C_p [%]	3.42	10.7	0.5	6.8	23.2
Validation study 2					
x/R	1.5	2.0	2.5	3.0	3.5
Absolute deviation of streamwise velocity* [%]	6.8	8.0	9.8	11.7	12.3
Absolute deviation of lateral velocity* [%]	2.8	2.5	2.3	2.2	2.3
* averaged over the lateral direction					
Validation study 3					
θ	90°	108°	133°	158°	223°
Absolute deviation from the experiment [%]	31.1	11.6	4.5	16.6	7.4
Reported uncertainty in the experiment [%]	20.2	11.0	12.5	17.5	31.1

Fig. 8. Variations of time-averaged (over the last turbine revolution) experienced angle of attack and relative velocity normalized by $V_{norm} = U_\infty \sqrt{1 + \lambda^2}$.

interaction between the shed DSV and the incipient TEV further complicates the flow on the blade. The TEV can be recognized by a suction imprint on the surface pressure contour plot (see Fig. 9), but also as a region of positive skin friction values (see Fig. 10) near the trailing edge. The following points regarding the TEV are noted:

- Formation of the TEV:** Both the SAS and URANS predict an earlier formation of the TEV, compared to the reference case, while this is more pronounced for URANS.

- Size and strength of the TEV:** The predicted size and strength of the TEV by SAS are considerably closer to the reference case predictions, than URANS. A large difference can be seen for the URANS predictions compared to the reference case.

- Shedding of the TEV:** URANS predicts noticeably earlier shedding of the TEV compared to the reference case, while the SAS prediction is in line with the reference case.

The aforementioned results clearly indicate that SAS is capable of providing closer predictions to the reference case than URANS, with respect to the formation of the DSV and TEV, shedding of the TEV, the size and the strength of the TEV. In addition, after the DSV shedding, SAS predicts a secondary vortex, rather than secondary and tertiary vortices as predicted by URANS. As a result of these, SAS provides a prediction of the flow pattern during the downstroke (decreasing α) almost in line with the reference case. URANS however predicts a considerable reverse flow over the blade during the downstroke, which is largely different from the reference case predictions.

Fig. 12 illustrates the contour plots of the z-vorticity non-dimensionalized with the blade chord length and $U_\infty \sqrt{1 + \lambda^2}$, at different azimuthal positions, i.e. $\theta = 70^\circ, 80^\circ, 90^\circ, 100^\circ, 110^\circ$ and 120° . It can be seen that:

- At $\theta = 70^\circ$, the DSV is already formed near the leading edge based on the URANS predictions while the SAS flow prediction is closer to that of the reference case where the LSB is still not burst.
- At $\theta = 80^\circ$, the size of the DSV predicted by SAS is noticeably closer to the reference case.
- At $\theta = 90^\circ$, both SAS and the URANS predictions show that the DSV is already disconnected from its feeding sheet emanating from the blade leading edge, as opposed to the reference case. In addition, the following DSV characteristics, namely the size, the chordwise distance to the leading edge, and the normal distance to the blade surface, predicted by the reference case are smaller than the predictions by URANS and SAS. Compared to the reference case, SAS predicts a larger normal distance of the DSV to the blade surface implying an earlier shedding of the DSV.
- At $\theta = 100^\circ$, the URANS and the SAS predictions show that a secondary vortex is already formed while this does not corroborate with the reference case, where the DSV is still connected to its feeding sheet emanating from the blade leading edge.
- At $\theta = 110^\circ$, the DSV in the reference case is still connected to its feeding sheet emanating from the blade leading edge and is about to leave the blade. URANS predicts the formation of a tertiary vortex which is being stretched due to the proximity to the already-shed secondary vortex. SAS predicts merging of the already-shed dynamic stall and secondary vortices in close proximity and consequent

Fig. 9. Spatiotemporal contours of surface pressure coefficient along the blade suction side (see Fig. 2) at mid-span during half-revolution. LE: leading edge; LSB: laminar separation bubble; DSV: dynamic stall vortex; SV: secondary vortex.

Fig. 10. Spatiotemporal contours of skin friction coefficient along the blade suction side (see Fig. 2) at mid-span during half-revolution. TE: trailing edge; LSB: laminar separation bubble; DSV: dynamic stall vortex; SV: secondary vortex; TEV: trailing-edge roll-up vortex.

formation of a larger vortical structure. The predictions by SAS and URANS are largely different from that of the reference case. Regarding the TEV, both URANS and SAS predict a larger size of the TEV compared to the reference case where this is more pronounced for URANS. In addition, URANS predicts that the TEV is already elevated from the blade surface as opposed to the reference case.

- At $\theta = 120^\circ$, the SAS-predicted size of the TEV is significantly closer to the reference case than URANS.

It can be concluded that SAS is capable of providing closer predictions to the reference case than URANS, mainly with respect to the size of the DSV and the TEV. However, an important shortcoming of

URANS, which seems to also hold for the SAS, is the early prediction of the disconnection of the DSV from its feeding sheet emanating from the blade leading edge, compared to the reference case, which later results in the formation of the secondary/tertiary vortices.

Figs. 13a-b and 14 show the lift and drag coefficients, C_l and C_d , versus azimuth θ and α during the turbine half-revolution calculated using Eqs. (3) and (4), where C_{Ft} , C_{Fn} , U_∞ , d , h , c , and S are coefficient of turbine tangential and normal loads, freestream velocity, turbine diameter and height, blade chord length and domain span, respectively. $\alpha(\theta)$ and $V_{rel}(\theta)$ are the experienced angle of attack and relative velocity as a function of θ as presented in Fig. 8. Note that although the blade cross-section is a symmetric NACA0015, it behaves as a cambered

Fig. 11. Histories of surface pressure coefficient at selected chordwise positions along the blade suction side at mid-span during half-revolution.

airfoil due to the virtual cambering caused by the flow curvature effects [104], which is present due to the rotation of the blades of VAWTs. This explains the positive values of C_l at α equal to zero or small negative values.

$$C_l(\theta) = [C_{Fl}(\theta)\sin[\alpha(\theta)] + C_{Fn}(\theta)\cos[\alpha(\theta)]] \frac{U_\infty^2}{V_{rel}(\theta)^2} \frac{dh}{cS} \quad (3)$$

$$C_d(\theta) = [-C_{Fl}(\theta)\cos[\alpha(\theta)] + C_{Fn}(\theta)\sin[\alpha(\theta)]] \frac{U_\infty^2}{V_{rel}(\theta)^2} \frac{dh}{cS} \quad (4)$$

Fig. 13c–d illustrate the relative difference between the URANS and the SAS predictions of the turbine blade aerodynamics loads with the

reference case. The comparison presented in Figs. 13 and 14 shows that:

- Regarding C_l , the absolute differences between URANS and the reference case on the one hand and SAS and the reference case on the other hand, are comparable, see Fig. 13c. The mean (over the half-revolution) difference with the reference case is 15.5% for URANS and 16.6% for SAS.
- Regarding C_d , the absolute differences between SAS and the reference case are considerably lower than between URANS and the reference case, see Fig. 13d. This is especially the case in the downstroke, i.e. $\alpha > \alpha_{max}$. The mean (over the half-revolution) difference with the reference case is 27.6% for the URANS and

Fig. 12. Contour plots of z-vorticity non-dimensionalized with chord length and $U_{\infty} \sqrt{1 + \lambda^2}$ at different azimuthal positions. DSV: dynamic stall vortex; SV: secondary vortex; TEV: trailing-edge roll-up vortex.

21.1% for the SAS.

- Prior to the LSB bursting ($\theta \approx 60^\circ$ – 70°), see Figs. 9 and 10, lift predictions by URANS and SAS are overlapping with the reference case. The drag prediction by URANS is overlapping with that of the reference case while SAS predicts comparatively (marginally) higher drag.
- After the LSB bursting by the formation of the DSV and prior to the DSV shedding ($\theta \approx 79^\circ$ – 96°), lift and drag values predicted by both SAS and URANS are higher than the reference case. This could be attributed to the earlier LSB bursting predicted by SAS and URANS resulting in a DSV with a larger size at identical θ and consequently a larger impact on lift and drag values. At $\theta \approx 96^\circ$ corresponding to the instant of the DSV shedding as predicted by the reference case, the SAS-predicted C_l and C_d values are approximately 0.50 and 0.16 higher than the reference case, respectively. These values for the URANS are approximately 0.62 and 0.35.
- The stall angle and the respective maximum lift and drag values

predicted by the SAS and the URANS are lower than that of the reference case. This is because both approaches predict an earlier shedding of the DSV, compared to the reference case. The predicted stall angles for URANS and SAS are approximately 84° and 88° while this value is around 96° for the reference case.

- After the stall up to the instant where the DSV meets the incipient TEV, both SAS and URANS predictions of lift and drag are lower than the reference case. Note that the predicted drag by the SAS is closer to that of the reference case than that by URANS. This is due to the predictions of the TEV size and strength by the SAS that are closer to those of the reference case.
- By the formation and the growth of the TEV, a sudden increment in lift is observed where the peak occurs at the instant of shedding of the TEV. The formation of the TEV is also accompanied by an abrupt jump in drag followed up by a sudden drop prior to the instant of the shedding of the TEV. The predicted lift values by both SAS and URANS do not agree with the reference case, which could be due to

Fig. 13. (a-b) lift and drag coefficients and (c-d) their absolute difference with respect to the reference during half-revolution.

the complexity of modeling of the interaction between the incipient TEV and the shed DSV during the sharp downstroke. The drag predicted by URANS remains largely different than that of the reference case during the whole downstroke while the SAS predictions are noticeably closer to the reference case during the formation and growth of the TEV and the SAS-predicted values almost overlap with those of the reference case after the TEV shedding. As mentioned before, this is because the SAS-predicted TEV characteristics are more consistent with those of the reference case.

It can be concluded that compared to URANS, SAS is capable of providing closer predictions of the aerodynamic loads on the turbine blade to the reference case, specifically the drag predictions during the downstroke.

5.2. Turbine loads

In this section, the turbine tangential and normal load predictions by the three approaches are compared. The turbine instantaneous tangential load presents the effective combined influence of the blade aerodynamic loads rotating the turbine, therefore, is one of the crucial power performance parameters. The turbine normal loads are also of importance for structural reasons.

Fig. 15a and b show the coefficients of the turbine instantaneous

tangential and normal loads, C_{F_t} and C_{F_n} , calculated using the URANS, SAS and SBES (reference) approaches during the half-revolution. Fig. 15c and d show the absolute difference between the URANS- and the SAS-predicted C_{F_t} and C_{F_n} values with those of the reference case. It can be seen that:

- Regarding the C_{F_n} , the difference between the predictions of the URANS and the SAS with that of the reference case are comparable, where such differences are slightly smaller for the SAS just prior to and post stall;
- Regarding the C_{F_t} , during the upstroke (i.e. $\theta < 117^\circ$), the predictions of URANS are closer to the reference case than the SAS. On the other hand, during the downstroke (i.e. $117^\circ \leq \theta \leq 180^\circ$) the reverse happens and the predictions of the SAS are significantly closer to the reference case. The smaller differences between the SAS-predicted C_{F_t} values with the reference case during the downstroke is consistent with the comparative agreement of the SAS-predicted TEV characteristics and aerodynamic loads with the reference case at identical θ .

6. Discussion

The computational cost of the simulations performed using the three approaches is largely different (see Table 3). Compared to SAS, URANS simulations are performed using a computational grid with ~ 4 times

Fig. 14. Lift and drag coefficients versus angle of attack during half-revolution ($\circ$: $\theta = 0^\circ$; $\triangle$: $\theta = 90^\circ$; $\diamond$: $\theta = 180^\circ$).

less number of cells and a time step that is 20 times coarser while the SBES simulations are performed on a computational grid almost two times finer and with the same time step as SAS. The total wall-clock time for one full turbine revolution for the SAS and the SBES simulations are ~ 24 and ~ 43 times of the URANS, respectively.

The present study provides a comparative analysis between the three numerical approaches, namely URANS, SAS and SBES for the complex case of flow on a VAWT blade in dynamic stall. The comparison highlights the aspects of SAS as an approach to bridge the gap between the URANS and the hybrid RANS-LES approaches. Indeed, in case of availability of high-spatiotemporal-resolution low-uncertainty experimental data, a stronger argument can be made by direct comparison of the three approaches against the experiment. However, at this stage, this was not the case and therefore, the more advanced hybrid RANS/LES approach, i.e. SBES, was employed as the reference for the comparative analysis.

The findings of the presented detailed comparative analysis can be employed to further improve the SAS approach for the prediction of the dynamic stall phenomenon. In addition, the revealed shortcomings of the URANS can be used to fine-tune the Reynolds-averaged turbulence models for CFD simulations of VAWTs.

Note that a comprehensive set of solution verification analyses has been performed for URANS simulations where the impact of various computational settings, e.g. domain size, grid resolution, azimuthal increment, convergence criterion and Reynolds-averaged turbulence

model, are systematically investigated. The scale-resolving simulations (SAS and SBES) are also performed based on the available best-practice guidelines. This, to a large extent, ensures that the difference in the prediction of the models is mainly because of the models themselves rather than the rest of the computational settings.

7. Conclusions

The Scale-Adaptive Simulation (SAS) approach, formulated using the four-equation transition SST turbulence model, is employed to analyze the complex case of unsteady separation and dynamic stall on a vertical axis wind turbine blade, which inherently undergoes simultaneous large excursions of the angle of attack and the relative velocity. The turbine has a blade cross-section of NACA0015 airfoil and operates at a chord-based Reynolds number of 5×10^4 and a reduced frequency of 0.125.

The SAS results are compared against that of less-accurate commonly-used URANS and a more advanced computationally-expensive hybrid RANS/LES approach, namely Stress-Blended Eddy Simulation (SBES), in order to investigate the promised made by the SAS approach to bridge the gap between the URANS and the hybrid RANS/LES approaches. The evaluation is based on detailed analyses of the blade aerodynamics and the turbine performance.

The results show that the SAS, compared with the URANS, is capable of providing closer predictions to the SBES approach with respect to the following items:

- The instant of the bursting of the LSB;
- The instant of the leading-edge suction collapse;
- The instant of the formation of the DSV and the TEV;
- The instant of the shedding of the TEV;
- The size of the DSV;
- The size and the strength of the TEV;
- The number of post-DSV vortices;
- The drag prediction during the downstroke.

However, on several other aspects both SAS and URANS fail to corroborate with the SBES predictions. These include:

- The instant of the formation of the LSB;
- The chordwise extent of the LSB;
- The instant of the disconnection of the DSV from its feeding sheet emanating from the blade leading edge and the DSV shedding;
- The stall angle;
- The drag jump by the shedding of the DSV;
- The lift values after the stall in the upstroke and the whole downstroke.

On the turbine scale, during the upstroke (i.e. $\theta < 117^\circ$), the comparative agreement of the SAS with the SBES predictions of the turbine instantaneous tangential loads is even slightly inferior to that of URANS. On the other hand, for $\theta \geq 117^\circ$ (corresponding to the downstroke), the SAS predictions are almost in line with those of the SBES while the URANS predictions are largely different. Regarding the turbine instantaneous normal loads, the difference between the predictions of URANS and SAS with that of the SBES are comparable.

The observations highlight the importance of accurate prediction of the dynamic stall characteristics (i.e. formation, growth, bursting/shedding of the LSB, DSV, TEV, their interactions, the drag values during the downstroke) on the overall power performance prediction of wind turbines at low tip speed ratios.

Fig. 15. (a-b) tangential and normal force coefficients of the turbine and (c-d) their absolute difference with respect to the reference during half-revolution.

Table 3

Comparison of computational cost of the three models (Number of CPUs = 72, CPU: Intel(R) Xeon(R) E5-2690 v3, memory: 320 GB).

Model	Number of cells	dθ [°]	Number of timesteps per turbine revolution	Number of iterations per timestep	Total wall-clock time for 1 turbine revolution [hr]
2.5D URANS	4,782,010	0.1	3600	20	17.5
2.5D SAS	19,753,402	0.05	72,000	2	408.6
2.5 SBES	37,417,411	0.05	72,000	2	741.9

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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