DYNAMIC STALL MODEL OPTIMIZATION WITH CFD AND ASSESSMENT WITH COMPREHENSIVE APPROACH FOR IMPROVED BLADE DESIGN

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Abstract

An enhancement for comprehensive modelling of rotor in forward flight is proposed to enable inclusion of dynamic stall and study characteristic effects on rotor loads and performance in design phase. The characterization of dynamic stall behavior of the selected airfoil on the design is performed with validated CFD analyses. Parameter optimization is performed for the dynamic stall and unsteady aerodynamics model in CAMRAD II, comprehensive analysis tool, to attain maximum similarity with CFD based predictions. Optimized dynamic stall model is then utilized to study rotor loads at dynamic stall dominated flight condition. Using the improved analysis framework with optimized dynamic stall model, the effect of anhedral tip shape on blade loads and stall onset characteristics is studied. It is observed that, anhedral modification to a blade tip combined with dynamic stall phenomena, worsens rotor torsional loads. On the other hand, application of an up-wash twist at tip anhedral region, improves the degraded load characteristics. The aim of this study is practice estimation of dynamics stall characteristics of an airfoil of interest with CFD, optimize dynamic stall model in accordance and investigate effect on rotor loads in the presence of anhedral.

1. INTRODUCTION

The cyclic blade motion and complex three-dimensional flow characteristics for a helicopter rotor in forward flight constitutes a well-matched environment for blade sections to experience dynamic stall phenomena. Especially in highly loaded high speed forward flight conditions with large control inputs, the oscillating blade sections experiences a peculiar hysteresis variations in aerodynamic coefficients when effective angle of attack values exceeds locally the static stall angle [1].The ability to predict dynamic stall behavior and implement into comprehensive rotor modelling tools successfully enables a better representation of rotor large unsteady and vibratory loads which in general determines maximum control loads, aeroelastic stability and fatigue limits [2].

At a typical rotor design phase, a broad variety of flight conditions and maneuvers are required to be simulated. Those simulations are required to be performed employing full helicopter trim where pitch link loads, blade root and rotor vibratory loads that drive stall onset characteristics, are of interest. Such assessments are currently performed with comprehensive modelling tools where advanced aerodynamic phenome such as dynamic stall is represented with empiric/analytic models. Those models are generic mathematical representations including several tuning parameters and time constants specific to each airfoil. Where plenty of airfoils are assessed rapidly, proper dynamic stall representation of each airfoil within the comprehensive modeling tools is essential in order to study rotor loads accurately and compare design alternatives.

Additionally, literature data on how a typical anhedral modification to blade tip geometry affects rotor vibratory loads are contradicting or not explicit. Such that, some studies propose addition of an anhedral worsens rotor mean and oscillatory loads [6] whereas some studies shows improvement in mean loads while worsening in oscillatory loads or vice versa [7], [8] while keeping or improving total aerodynamic performance of the rotor. Main reason for this blur is evaluated to be the necessity of high fidelity simulations such as CFD-CSD coupled approaches with aeroelastic and full helicopter trim contributions included. Instead, presently such evaluations are being performed with simplified approaches or comprehensive modeling codes. Showing a broad diversity with diverse modeling assumptions, comprehensive tools display significant difference between calculated vibratory loads [5], [8]. Furthermore as anhedral is applied to the blade tip which is also the region dynamic stall phenomena typically dominates[10], the tool utilized to assess effect of anhedral on rotor vibratory loads shall also be capable of resolving dynamic stall behavior to an extent.

It is obvious that dynamic stall characteristics for each airfoil assessed will not be available during the design phase. Besides estimating with proper tests bring enormous workload and cost[9]. Therefore, unsteady CFD as an indispensable alternative, and is utilized to estimate dynamic stall behavior for airfoils of interest in this study. Then parameters for the dynamic stall models present in comprehensive modeling tool CAMRAD II are tuned with an optimization approach to represent the estimated post stall unsteady aerodynamic lift, drag and pitching moment characteristics. Optimized model is then utilized to evaluate the effect of dynamic stall on rotor torsional loads for various flight and operating conditions. The effect of anhedral tip geometry on aerodynamic efficiency and noise levels has

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already been studied[4]. In this study the effect of anhedral on pitch link and rotor torsional loads for a blade operating under dynamic stall phenomena is studied.

2. VALIDATION OF CFD ANALYSIS FOR AIRFOIL DYNAMIC STALL

Unsteady CFD analyses are utilized to estimate dynamic stall behavior of the airfoil of interest which has a tab modification to ensure structural requirements. Yet, primarily, the CFD scheme utilized is validated for an airfoil for which dynamics stall characteristic data is present in the literature [11], depicted in Figure 1.

The CFD analyses for dynamic stall characteristic evaluation are performed by ANSYS Fluent software where pitching motion of the airfoil is modeled in 2-D domain with overset grid topology. URANS equations are solved with k-w SST turbulence model with properly refined mesh near airfoil geometry with aiming y+ value less than one.

3. METHODOLOGY FOR ESTIMATION OF DYNAMIC STALL & UNSTEADY AERODYAMIC MODEL PARAMETERS

Parameter optimization for Leishman-Beddoes dynamic stall and Leishman-Beddoes unsteady aerodynamic models that exists in CAMRAD II is performed. Optimization is performed in accordance with CFD predictions of the oscillating airfoil of interest. A design of experiment optimization method with Latin Hypercube sampling approach[12] is utilized to estimate values for related parameters. Considering both dynamic stall and unsteady aerodynamics models, a total of 20 parameters are identified and operated to minimize a cost function describing dynamic stall and post stall characteristics for the airfoil of interest.

Leishman-Beddoes dynamic stall and unsteady aerodynamics model determine contribution of delayed angle of attack and increments of lift and moment from the leading-edge vortex separately then superimposes to estimate aerodynamic coefficients of of-interest airfoil operating under dynamic stall phenomena. The basic representation of the model is summarized with equations (1),(2) and (3) for which detailed formulation is present in the literature [2] and [3].

$$c_l = \left(\frac{\alpha - \alpha_z}{\alpha_d - \alpha_z}\right) c_{l_{2D}}(\alpha_d) + \Delta c_{l_{DS}} + \Delta c_{l_{US}} \tag{1}$$

$$c_d = \left(\frac{\alpha - \alpha_z}{\alpha_d - \alpha_z}\right)^2 \left(c_{d_{2D}}(\alpha_d) - c_{dz}\right) + c_{dz} + \Delta c_{d_{DS}} + \Delta c_{d_{US}} \tag{2}$$

$$c_m = \left(\frac{\alpha - \alpha_z}{\alpha_d - \alpha_z}\right) \left(c_{m_{2D}}(\alpha_d) - c_{mz}\right) + c_{mz} + \Delta c_{m_{DS}} + \Delta c_{m_{US}} \tag{3}$$

Where α, α_z and α_s are the effective angle of attack, zero lift and stall angle of attacks, $c_{l_{2D}}$, $c_{d_{2D}}$ and $c_{m_{2D}}$ are two dimensional tabulated aerodynamic coefficients for airfoil of interest, α_d is the delayed angle of attack from unsteady flow. Increments in aerodynamic coefficients from leading edge vortex are included with $\Delta c_{l_{DS}}$, $\Delta c_{d_{DS}}$ and $\Delta c_{m_{DS}}$ terms. Delayed angle of attack and leading-edge vortex contributions are required as a function of Mach number for positive and negative angle of attack and are a function of airfoil specific parameters such as;

$$\alpha_d, \Delta c_{l_{DS}}, \Delta c_{d_{DS}}, \Delta c_{m_{DS}} = f\left(s_1, s_2, c_{l_{CR}}, c_{l_\alpha}, T_P, T_{vl}, T_v, T_f, x_s, \alpha_s\right) \tag{4}$$

Where, s_1, s_2 and x_s are airfoil specific constants, $c_{l_{CR}}$ is critical lift coefficient at the separation onset boundary, c_{l_α} is airfoil lift curve slope, T_P is dimensionless time constant, T_{vl} the time leading-edge vortex reaches the trailing edge, T_v time constant for moment increment, T_f time constant for additional lag in the boundary layer, α_s stall angle of attack.

On the other hand, parameters utilized, given with (5), for Leishman-Beddoes unsteady aerodynamics model in CAMRAD II for which detailed formulation can be found in the literature [2], [3], includes time constant factor for lift τ_{lift}, and moment τ_{mom}, lift-curve slope correction factor C_{cl_α}, stall delay factors for lift, drag and moment coefficients $K_{l,d,m}$, shift of aerodynamic center ΔX_{ac}, drag recovery factor ϵ_d, factor on angle of attack rate $C_{\dot\alpha}$ and a limit on angle of attack increment produced by stall delay $L_{\Delta\alpha}$.

$$\alpha_d, \Delta c_{l_{US}}, \Delta c_{d_{US}}, \Delta c_{m_{US}} = f\left(\tau_{lift}, \tau_{mom}, C_{cl_\alpha}, K_{l,d,m}, \Delta X_{ac}, \epsilon_d, C_{\dot\alpha}, L_{\Delta\alpha}\right) \tag{5}$$

4. RESULTS AND REMARKS

Given results are organized such that unsteady CFD simulations for the oscillating airfoil of interest under dynamic stall phenomena are illustrated first. Streamlines and instantaneous lift coefficients for oscillating airfoil of interest are illustrated with Figure 2 to Figure 9 for one full period of dynamic stall oscillation.

Then Leishman-Beddoes dynamic stall and unsteady aerodynamic model parameter tuning (optimization) is performed in accordance with CFD results is illustrated. Pitching moment for an airfoil is directly incorporated with root torsional moments and pitch-link loads for a blade which is then further identifies vibratory load and stall onset characteristics for a rotor. Therefore, the objective function operated through optimization is constituted such that the main interest is focused on pitching moment variations which is then followed by lift and drag. At Figure 10, 2-D airfoil results determined with optimized Leishman-Beddoes parameters are compared with the results determined with default Leishman-Beddoes model in CAMRAD II and CFD analyses. Then Rotor load variations for a typical dynamic stall dominated flight regime with dynamic stall model “off/on” with default (generic) parameters and “on” with optimized (tuned) parameters are studied. A typical dynamic stall dominated flight regime is anticipated to be at high blade loading and high forward speed. Therefore, CAMRAD II mathematical model of a typical 5-ton class helicopter is utilized to perform a trim analysis at high altitude, ambient temperature and forward speed. Under same trim conditions, pitching moment variations over one revolution at root and spanwise locations are investigated as depicted with Figure 11. Additionally, non-dimensional pitching moment and flap wise shear force variations are plotted with Figure 12.

The results where importance of dynamic stall model tuning is revealed are followed by the results for the effect of anhedral on rotor loads when dynamic stall model is off and on while at the same assessments, results for the design solution to reduce negative effect of a tip shape with anhedral are also considered. In this scope, spanwise and integrated pitching moment variations as well as effective angle of attack variations for blade without anhedral, with anhedral & dynamic stall off, with anhedral & dynamic stall on configurations are studied. In order to reduce negative effects of anhedral tip shape on rotor vibratory loads an additional configuration with an up-wash twist at the anhedral region is also considered and compared at Figure 13 and Figure 14.

In conclusion, inclusion of dynamic stall phenomena through a specifically tuned dynamic stall model within the comprehensive modelling tools for rotor load computations is evaluated essential. Typically, dynamic stall models are generic analytic/empiric mathematical representations with a variety of input parameters and time constants. At a rotor design phase, tuning those related parameters specifically to the airfoil utilized, modified or designed enables a better perspective to evaluate design alternatives in terms of rotor vibratory loads, pitch link loads and stall onset characteristics. To tune the models, oscillating post stall behaviour of airfoil of interest is prerequisite.

In this study, dynamic stall behaviour of the airfoil of interest is determined with unsteady CFD simulations which are then utilized with an optimization framework to tune Leishman-Beddoes dynamic stall model and Leishman-Beddoes unsteady aerodynamics model in CAMRAD II. Trim analyses at a dynamic stall dominated flight condition are performed with the optimized dynamic stall model to study its contribution to rotor loads. Then a typical anhedral modification is employed on the same rotor configuration to study its contribution to rotor loads. A possible design solution is proposed to eliminate observed negative effect the anhedral configuration.

At each stage of this study, various inferences have been achieved which can be summarized as;

- Inclusion of the dynamic stall model in CAMRAD II results in significant alteration of rotor loads, even used at its default setting (setting that is developed for NACA0012 profile)
- When optimized dynamic stall model is utilized instead of default model, around 2 times difference is observed in rotor torsional loads. Therefore, inclusion and tuning of a dynamic stall model specific to the airfoil of interest is essential in terms of rotor loads computed with comprehensive models.
- In the previous study, blade tip anhedral modification was evaluated to be favorable in terms of aerodynamic efficiency and aeroacoustics performance[4]. In this study on the other hand, it is observed that anhedral tip has negative effect on rotor torsional loads i.e. both mean and vibratory. This observation is found to be consistent with the literature work where wind tunnel tests have been performed for a blade with and without anhedral configurations [6].
- There possibly are numerous design solutions to alleviate negative effect of anhedral on rotor loads. Yet, in this study, a reverse twist (up-wash twist) in the anhedral region found to be favourable to eliminate or decrease negative contribution to the rotor torsional loads while keeping aerodynamic performance unchanged. This conclusion will further be practiced with higher fidelity simulation approaches to optimize blade tip with anhedral for low undesirable rotor vibratory loads.
- It is anticipated that dynamic stall dominates the outer %25 of the blade which is the same division for possible application of an anhedral tip modification, consistent with literature work [10]. Therefore, although inclusion of dynamic

stall in comprehensive analyses varies results significantly, when anhedral is considered, it is strongly advised to include and perform a parameter optimization for the dynamic stall model in the comprehensive codes specifically to the design of interest.

- It is experienced with this study that unsteady CFD simulations are indispensable in terms of estimating dynamics stall and post stall characteristics for airfoil designed, modified or for which literature data is absent [5].

There are numerous works on anhedral and how anhedral varies rotor loads in the literature. In this study we investigated how anhedral effects rotor loads under dynamic stall dominated operating condition. Analyses so far have been performed with CAMRAD II comprehensive modeling tool which is the best available approach until tests and higher fidelity CFD-CSD coupled, trim capable approaches mature enough.

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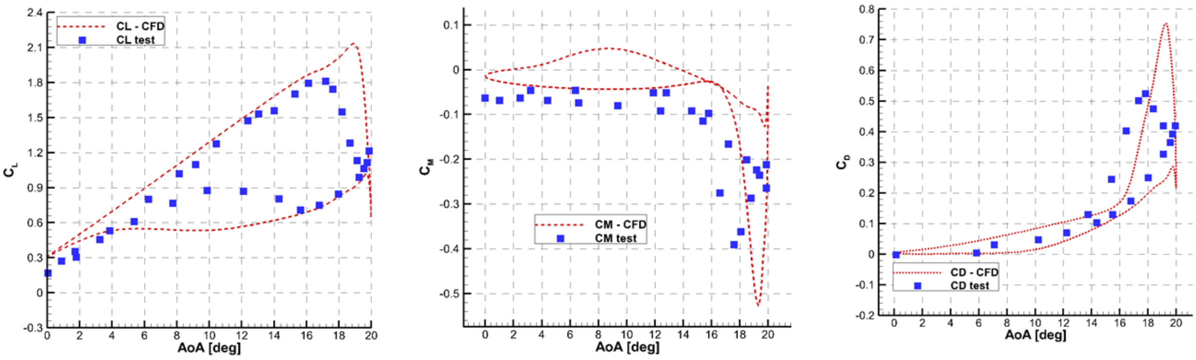

Figure 1 Test data versus CFD Results

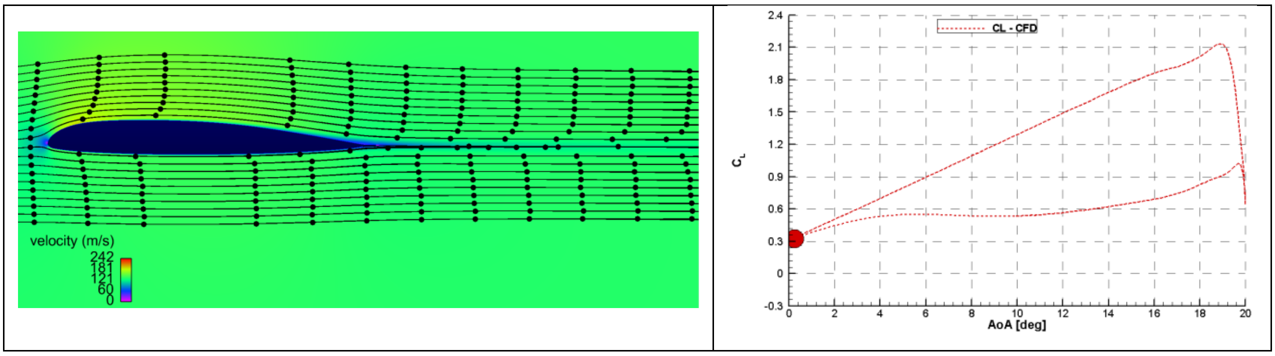

Figure 2 0 Degrees (ascending a.o.a)

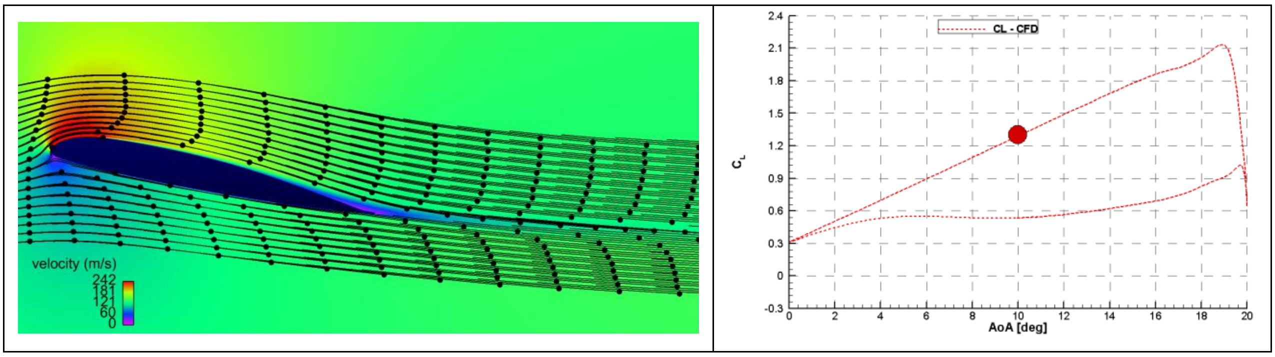

Figure 3 10 Degrees (ascending a.o.a)

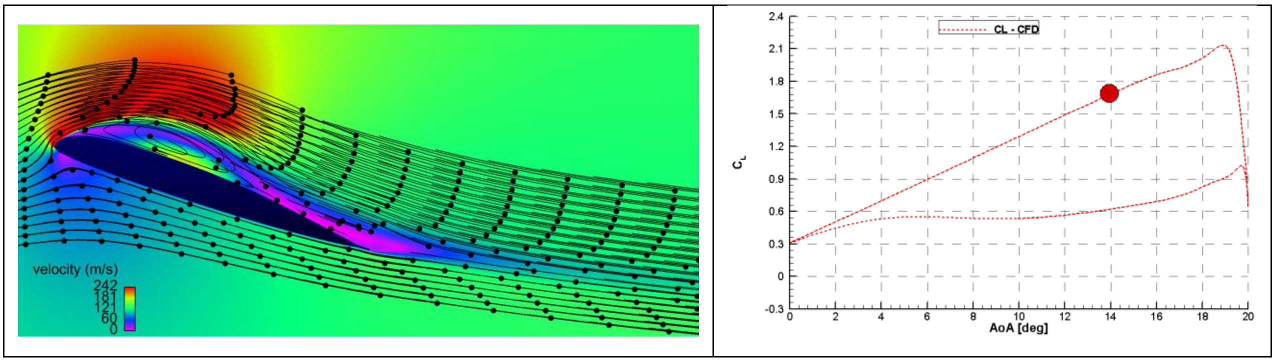

Figure 4 14 Degrees (ascending a.o.a)

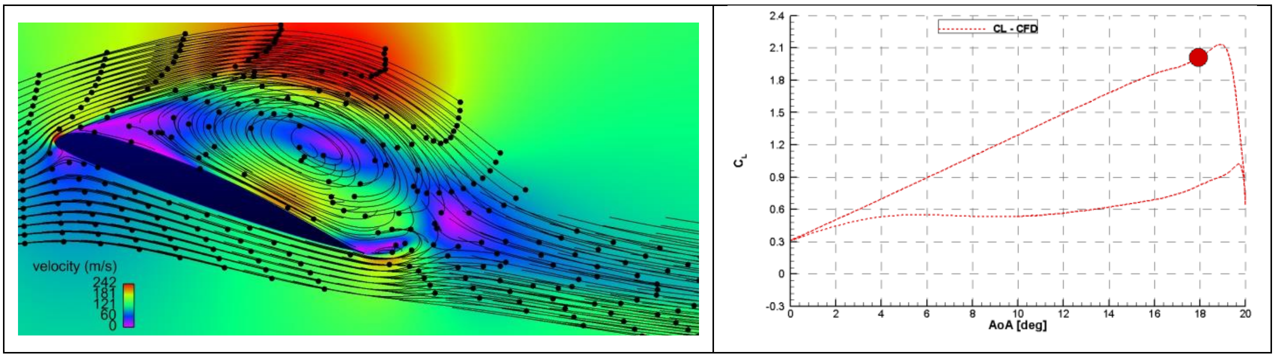

Figure 5 18 Degrees (ascending a.o.a)

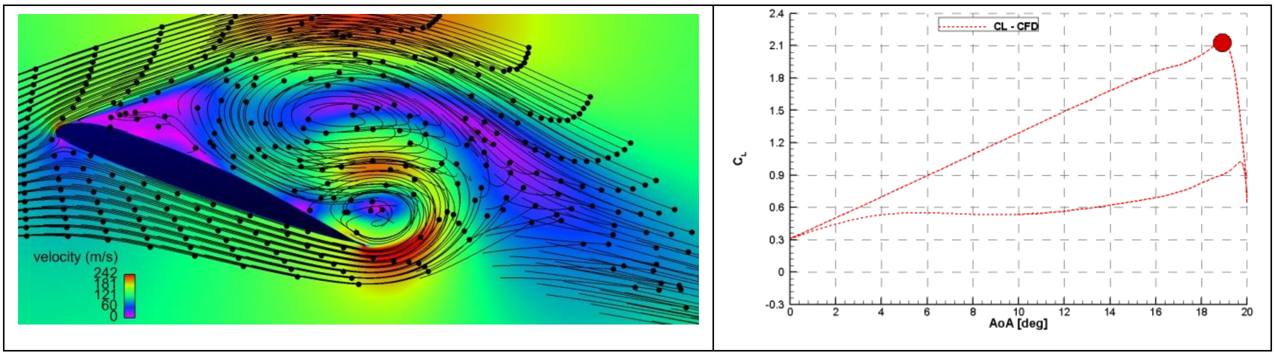

Figure 6 19 Degrees (ascending a.o.a)

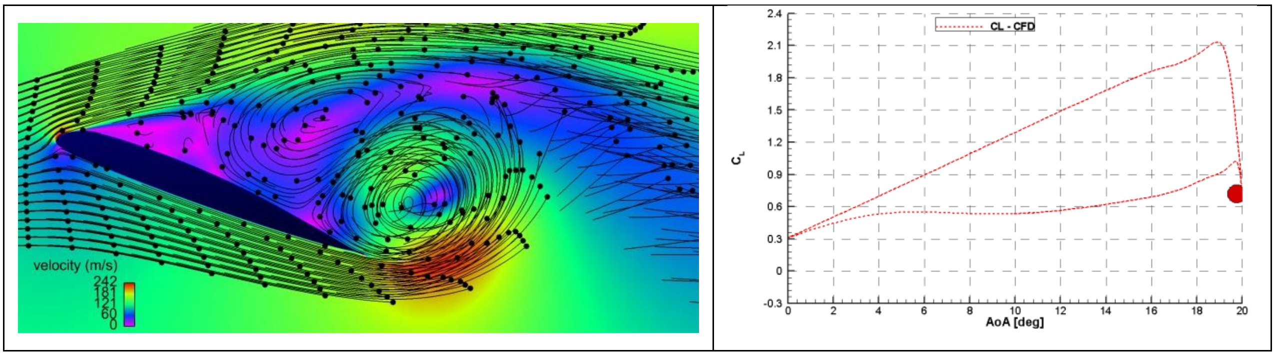

Figure 7 20 Degrees (ascending a.o.a)

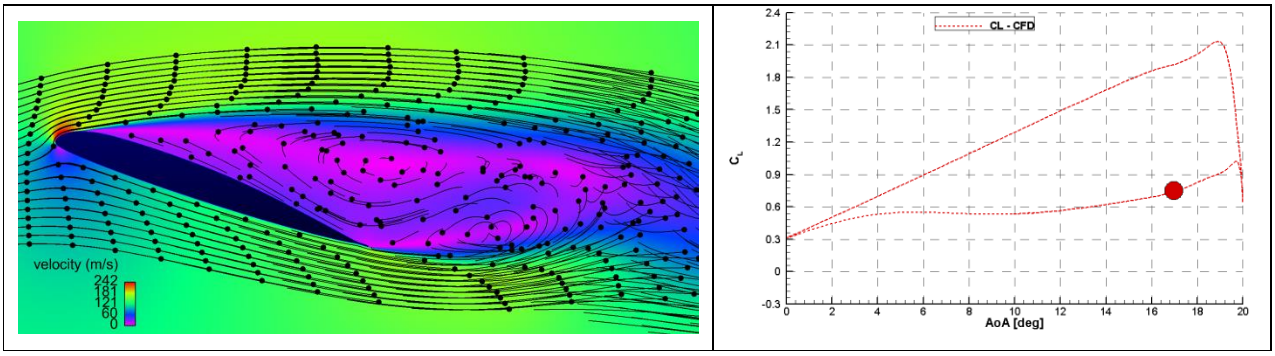

Figure 8 14 Degrees (descending a.o.a)

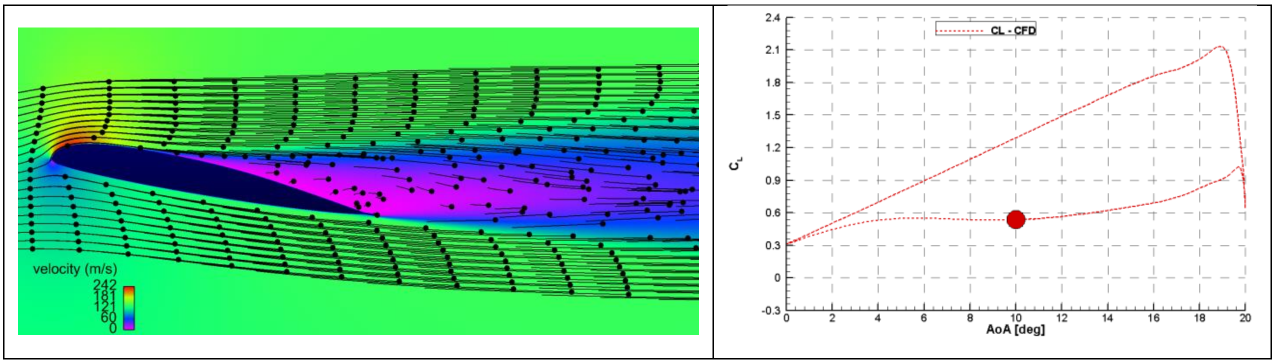

Figure 9 10 Degrees (descending a.o.a)

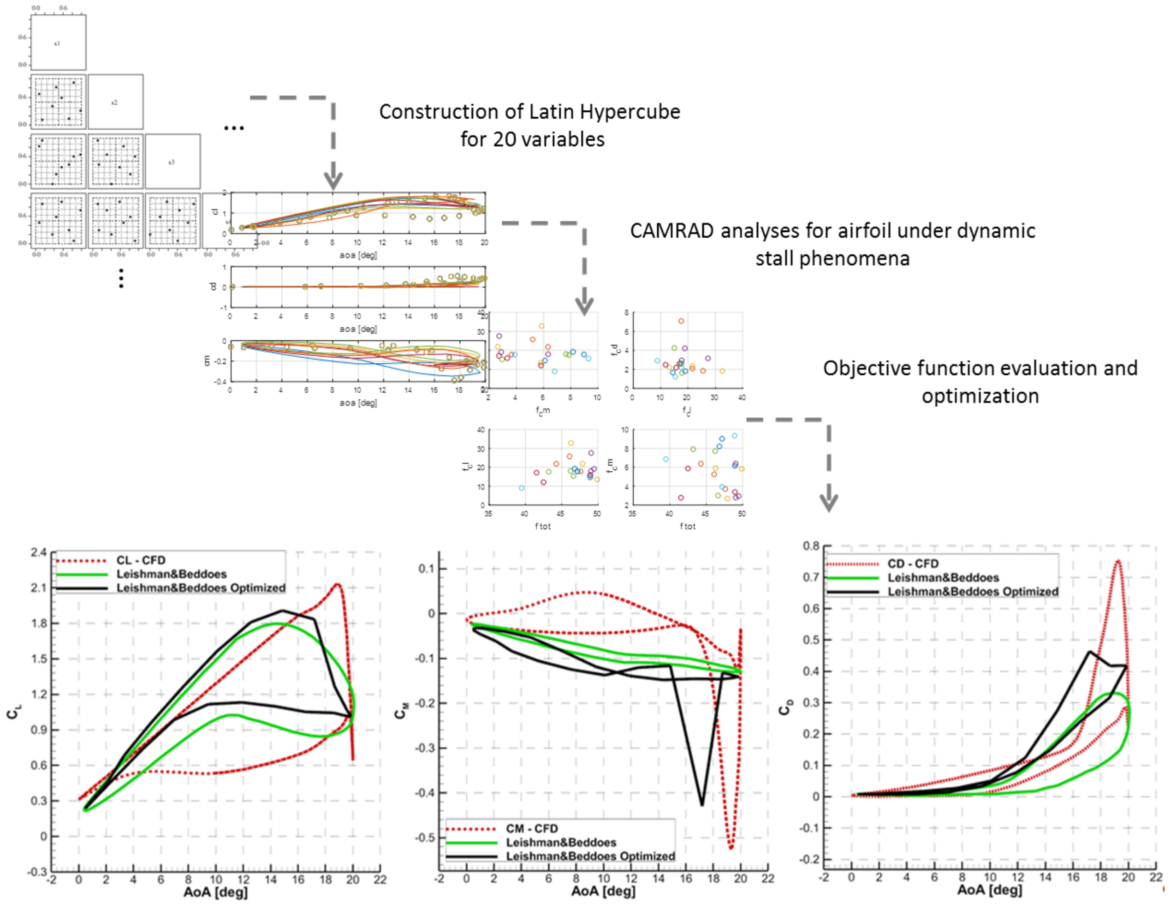

Figure 10 Response surface optimization scheme for dynamic stall model parameters in CAMRAD II

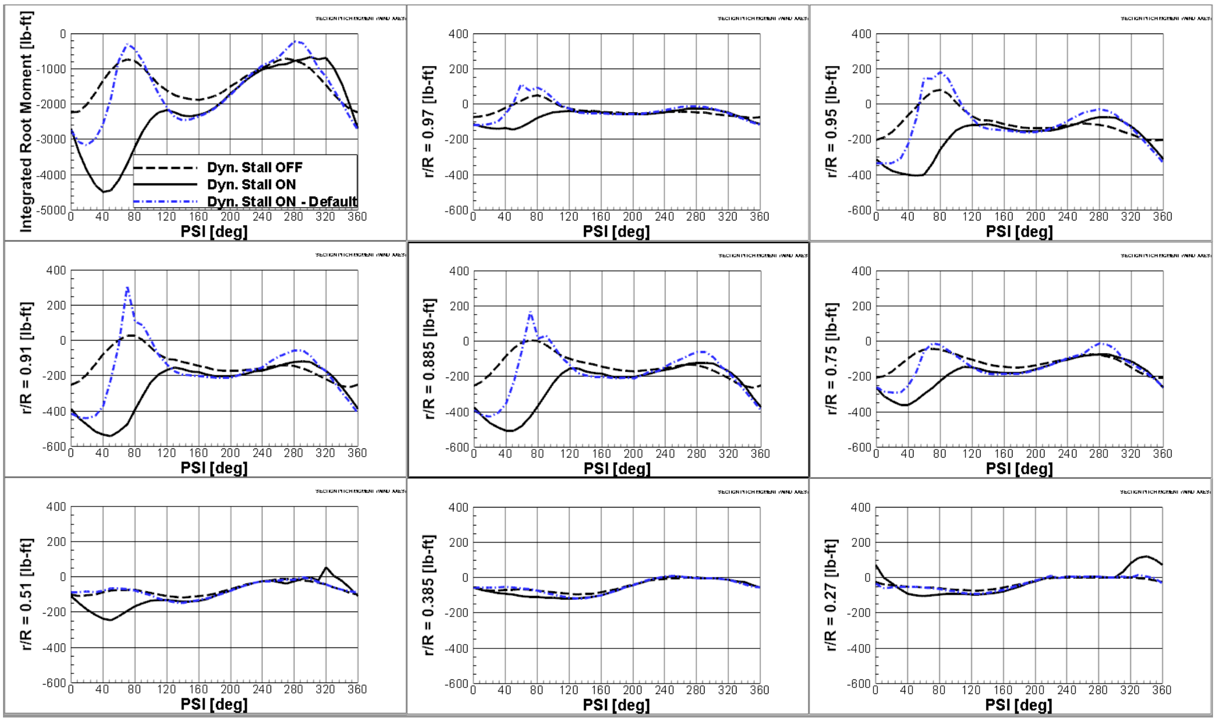

Figure 11 Pitching moment variations for dynamic stall model off and on conditions

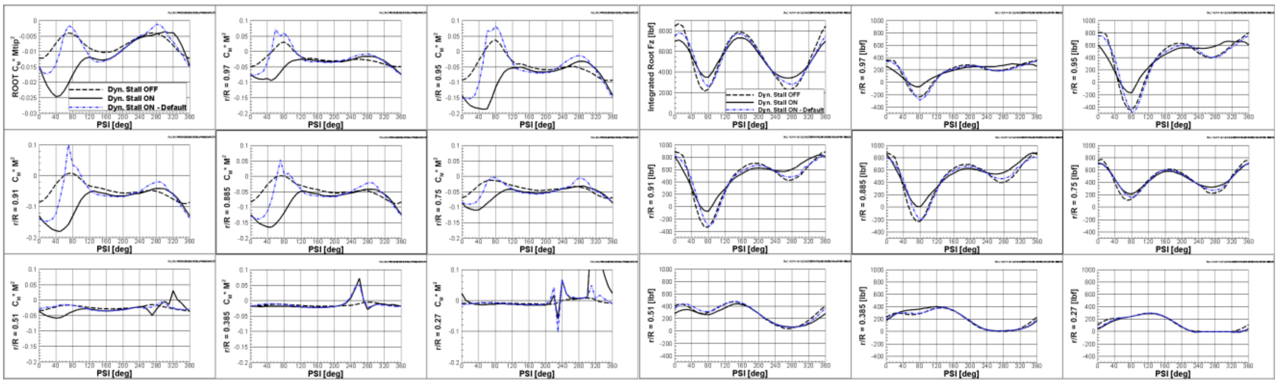

Figure 12 Non-dimensional Pitching moment and flapwise shear force variations

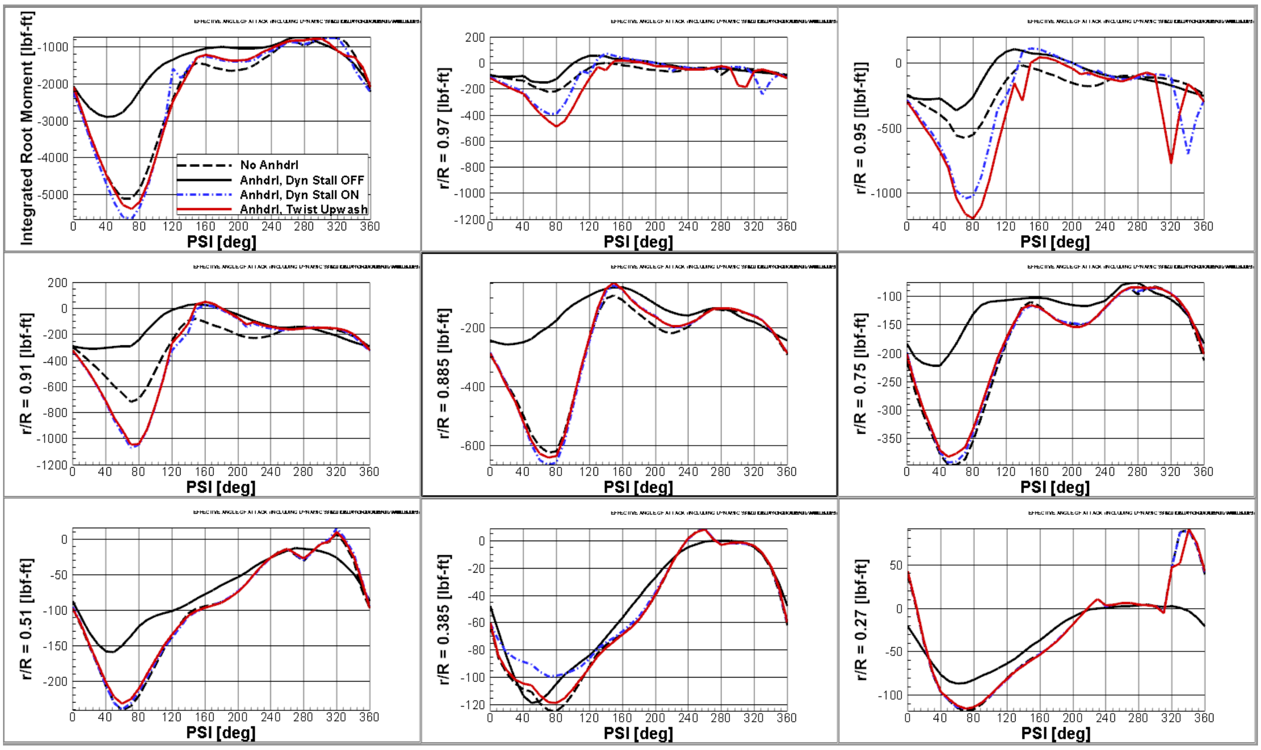

Figure 13 Pitching moment variations for anhedral case

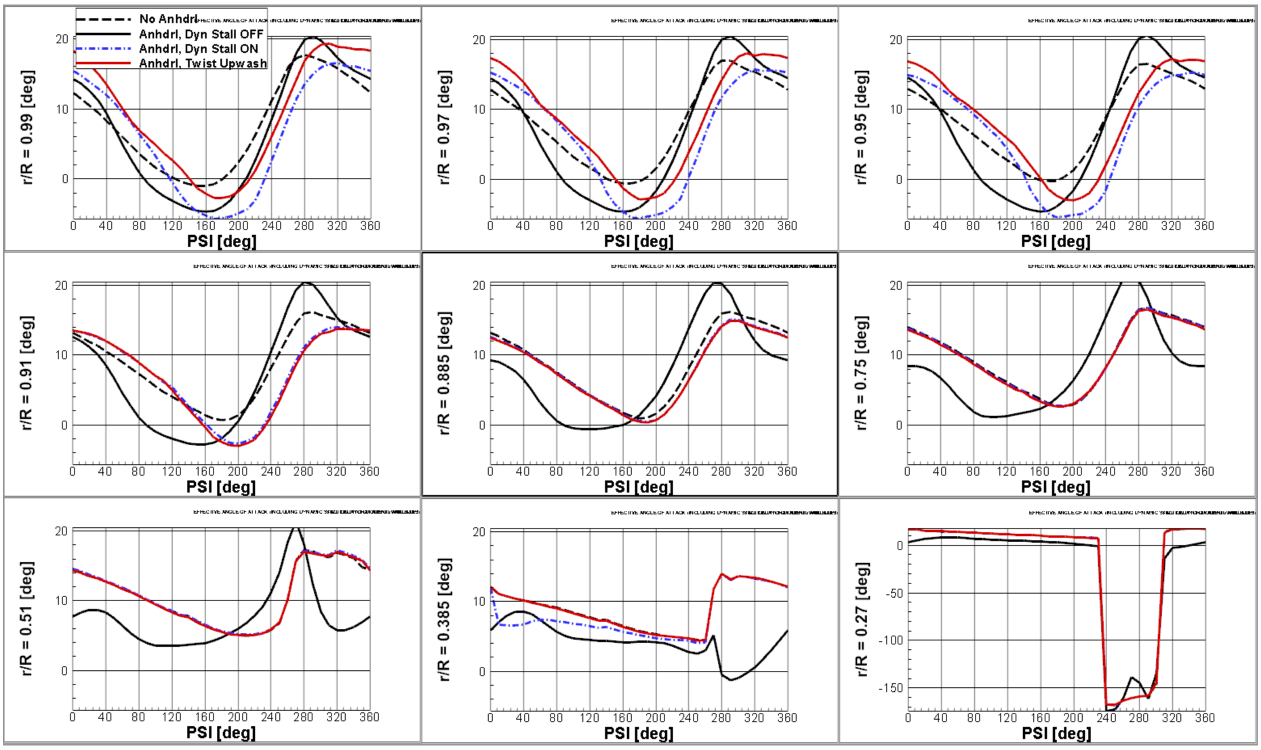

Figure 14 Effective angle of attack variations for anhedral case