EFFECT OF THREE DIMENSIONAL DYNAMIC STALL ON ROTORCRAFT STABILITY

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Abstract

Role of three dimensional dynamic stall in stability of rotorcraft is investigated here.Yawed flow and radial flow coupling between blade segments are included in the ONERA dynamic stall model and predictions for lead-lag damping are correlated with experimental data.Effect of each component of 3D effects are investigated individually.Yawed flow effect improves the correlation with experimental data significantly while radial coupling between blade segments alone show very little effect on lead-lag damping results. Contribution of dynamic inflow modelling in lead-lag damping prediction is also investigated. Dynamic wake effects plays a significant role and the 3D dynamic stall model with dynamic wake effects provides an excellent correlation with available experimental lead-lag damping data.

NOMENCLATURE

$C_{L_{max}}$	Maximum sectional lift coefficient
$C_{L_{max}(\Lambda=0)}$	Maximum sectional lift at zero yaw angle
$C_{L\alpha}$	Lift curve slope,rad^-1
C_T/σ	Blade loading
$\bar{r}$	non dimensional radial location from rotor center
α_S	Shaft tilt angle,deg
β	blade flapping angle,deg
Γ	Circulation per unit length
Γ_D	Circulation like Drag per unit length
Λ	Yaw angle(degree)
θ_0	Collective pitch angle,deg
μ	Advance ratio
ψ	Azimuth angle,deg

1 INTRODUCTION

Helicopters operating at extremes of flight envelope can have high blade loading under unsteady conditions leading to dynamic stall. Apart from loads and trim issues, this could also have serious impact on aero mechanical stability of the helicopter. Lead-lag motion of a helicopter blade is relatively less damped compared to the flapping motion of the blade and plays a major role in aero mechanical instabilities of helicopters. It is essential to accurately model the aerodynamic forces and moments of the rotorcraft at highly unsteady aerodynamic environment for the calculation of lead-lag damping. In this work,the effects of 3D dynamic stall on lead-lag stability of a helicopter rotor in forward flight is investigated. The results include a comparison of damping predictions using aerodynamic modelling of different complexities as well as with experimental data in Ref.[1].
In forward flight the aerodynamic environment of the rotor becomes complex due to dynamic stall, reverse flow and radial flow effects. Previous works on rotorcraft stability used dynamic stall models based on experimental work on airfoil sections which were unable to accurately predict lead-lag damping values, particularly at high advance ratios.
Ref.[2] predicted lead-lag damping for various combination of shaft tilt angles and collective input and also compared with experimental results of Ref.[1]. The damping results therein shows poor agreement with experimental data at high advance ratio. Specifically, it appears that the stall or dynamic stall model worsens the correlation, hinting that there is probably a stall delay not captured by the models. It may be noted that delays introduced in 2D models have also not been able to change the damping predictions significantly[3], and hardly any improvement in correlation is observed. This also raises the question, if dynamic stall model used has indeed captured dominant physical mechanisms. In summary the, computation of lead-lag damping in forward flight at high advance ratios require accurate dynamic stall model capturing three dimensional effects.

In this paper 3D effects, yawed flow and radial flow coupling between blade segments are investigated from the perspective of rotorcraft stability.Experimental work on yawed flow in 2D airfoil section[4][5] shows increase in maximum lift coefficient, $C_{L_{max}}$ with yaw angle(Λ) and delay in the occurrence of stall. Experimental work of dynamic stall of airfoil sections at yawed flow[6][7] shows delay in onset of dynamic stall and narrow hysteresis loop compared to without yawed flow,which implies that yawed flow cannot be ignored in dynamic stall modelling of rotorcrafts operating at high advance ratios. Ref.[8]and [9] suggested a simple expression to capture this increasing trend as a function of maximum sectional lift coefficient at zero yaw,$C_{L_{max}(\Lambda=0)}$ and yaw angle(Λ). However the expression had shortcomings such as infinite lift coeffcient at $\Lambda = 90°$ which had numerical issues when implemented in a dynamic stall model for a rotorcraft.Ref[10] suggested expression for maximum lift coefficient with yaw angle as a series of sinusoidal terms whose coefficients can be computed from the static lift characteristics of the airfoil section without yaw($C_{L\alpha}$,$C_{L_{max}(\Lambda=0)}$). The expression is continuous at all yaw angles and can be easily implemented in any dynamic stall model. Experiments[11] conducted on rotorcrafts in wind-tunnel shows radial flow coupling between blade segments of the rotor blade. Ref.[12] incorporated the radial flow coupling effect in dynamic stall equations in three dimensional dynamic stall modelling of rotorcrafts and the method is included in this work to investigate its effect on lead-lag damping correlation.

2 METHODOLOGY

Isolated rotor configuration[1] with only flap and lead-lag degrees of freedom is considered for the analysis. Dynamics of rotor-fuselage coupling and torsional degree of freedom of the rotor blades are not included throughout the analysis based on the experimental conditions of Ref.[1]. Experimental setup of Ref[1] does not have a swash plate and hence the rotor is operated at untrimmed condition with only collective input. Shaft tilt angle of the rotor was adjusted manually using a separate mechanism.Equilibrium solutions are obtained by solving the nonlinear coupled differential equations. Equilibrium solutions with and without 3D effects are also presented in the results section.

ONERA dynamic stall model[13] is used to find the unsteady aerodynamic forces and moments at rotor blade sections. The model also accounts for the reverse flow and large angle of attack at blade sections. Effect of yawed flow is included using the expression suggested by Ref[10].It is effectively dynamically changing the static lift characteristics of the blade airfoil section with instantaneous yaw angle which is calculated from the radial component of velocity. However this method assumes that there is no dynamic effects of the yawed flow in the lift coefficient of the airfoil section.

Effect of Radial flow coupling in dynamic stall equations is implemented by using the method of finite difference as given in Ref.[12].Small perturbation theory is used for the linearisation of equations of motion and stability analysis. Floquet theory is then used to compute the lead-lag damping values of the rotor in forward flight under stalled conditions(Ref.[14]).Both uniform inflow model from BEMT theory and dynamic inflow model are used and their effects on damping predictions are investigated. Peters-He dynamic inflow model(Ref.[15]) is used to capture the wake effects. Sufficient number of harmonics and radial shape functions are used to accurately compute the inflow.

3 RESULTS AND DISCUSSION

The 3D effects in equilibrium solution of the rotor is investigated in the following sections.Results obtained from the analysis is presented here for the case of zero collective pitch input($\theta_0 = 0°$) in which dynamic stall effects are more dominant compared to non zero θ_0.

3.1 Rotor Thrust Level Results

Figure 1-3 shows variation of thrust level(C_T/σ) with advance ratio for different shaft tilt angles. The plot shows that with 3D effects included in dynamic stall model, the results are close to linear theory results suggesting that the model is incorporating the stall delay effectively. The effect of radial coupling is much lesser compared to yawed flow on rotor thrust levels. The results however diverge from the linear theory results at high advance ratios with increase in shaft tilt angle.

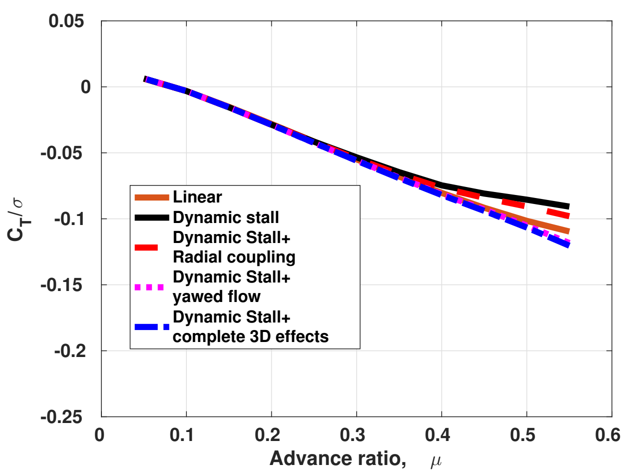

Figure 1: Thrust level variation with advance ratio $\theta_0 = 0°, \alpha_S = 12°$

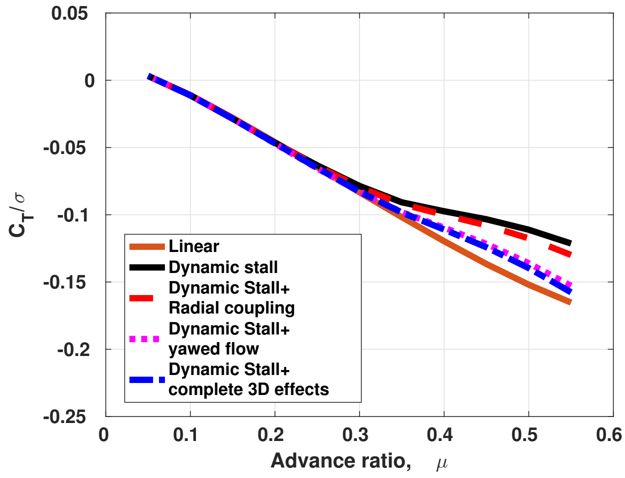

Figure 2: Thrust level variation with advance ratio $\theta_0 = 0°, \alpha_S = 16°$

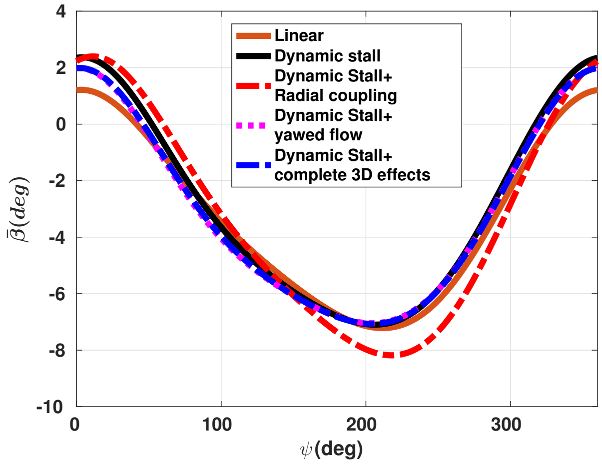

Figure 4: Periodic flap response($\theta_0 = 0°, \alpha_S = 12° \mu = 0.45$)

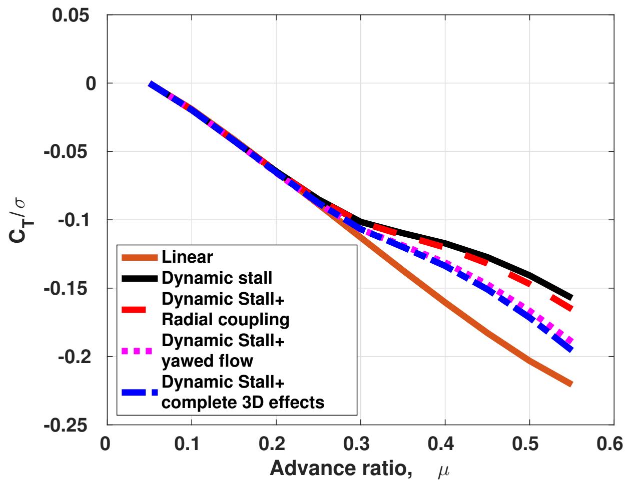

Figure 3: Thrust level variation with advance ratio $\theta_0 = 0°, \alpha_S = 20°$

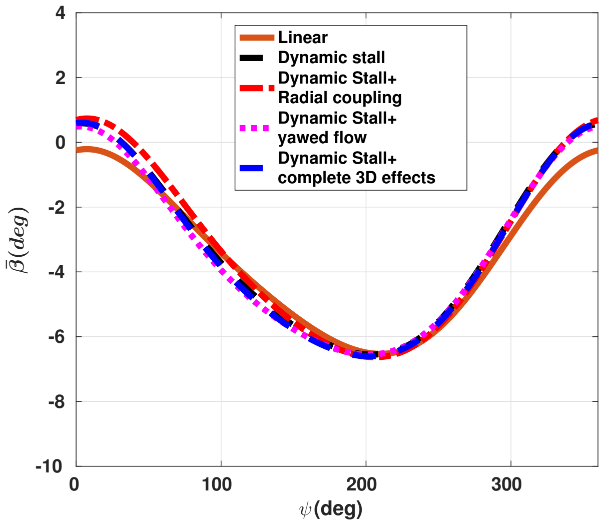

Figure 5: Periodic flap response($\theta_0 = 0°, \alpha_S = 16° \mu = 0.35$)

3.2 Periodic Response Results

In this section 3D effects on the periodic response of the rotor is investigated. Periodic solution of flapping, sectional lift coefficient are presented for zero collective input$\theta_0 = 0°$. The effect of yawed flow on drag coefficient of an airfoil section is negligible compared to lift coefficient and not shown in this investigation. Also the magnitude of lead lag equilibrium solution is small compared to flapping and neglected in this analysis. Results of periodic response in the region where yawed flow effects are dominant are presented below.

Figure 4-6 shows flapping response of a rotor blade for different shaft tilt angle at advance ratio where the 3D effects are dominant.It can be observed that three dimensional effects have very little impact on the periodic flapping response of the rotor. Next, the variation of sectional lift coefficient of a rotor blade over a revolution for the case of $\alpha_S = 12°$ at $\mu = 0.45$ is presented. Figure 7-10 shows the circulation (Γ) at different radial locations of a rotor blade. The 3D effects have more impact at inboard section of a rotor blade whereas they are negligible at outboard sections.

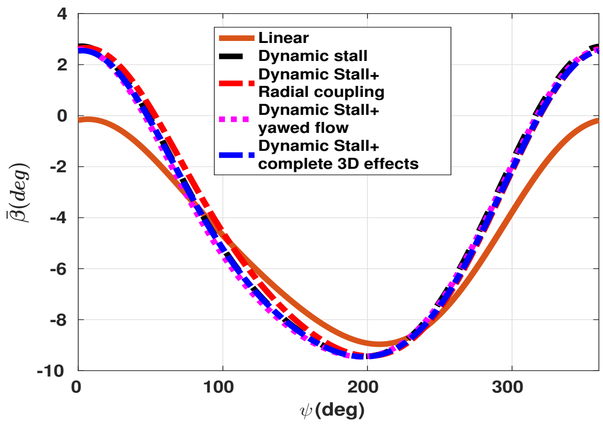

Figure 6: Periodic flap response($\theta_0 = 0°, \alpha_S = 20°, \mu = 0.35$)

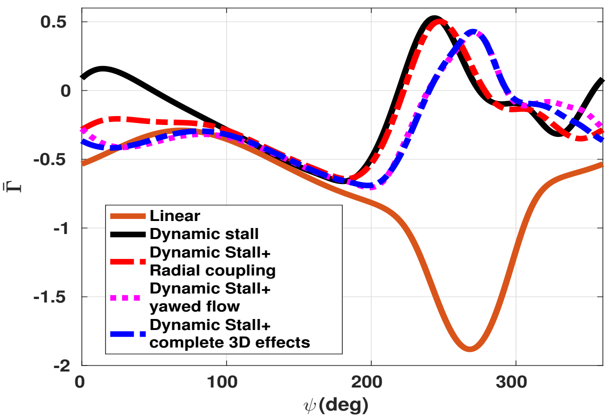

Figure 7: Circulation variation with azimuth angle, $\alpha_S = 12, \theta_0 = 0°, \mu = 0.45, \bar{r} = 0.36$

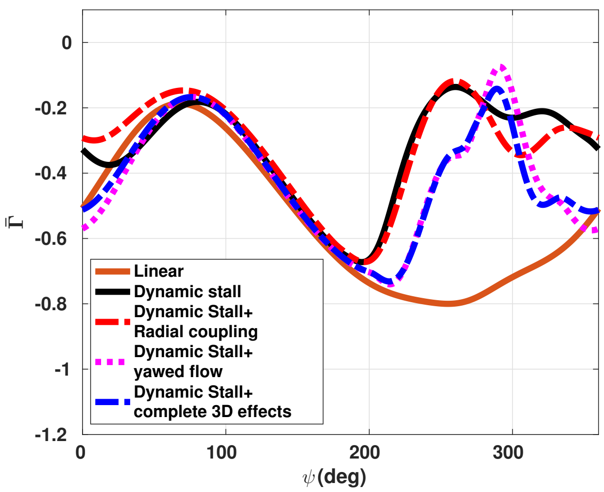

Figure 8: Circulation variation with azimuth angle, $\alpha_S = 12, \theta_0 = 0°, \mu = 0.45, \bar{r} = 0.56$

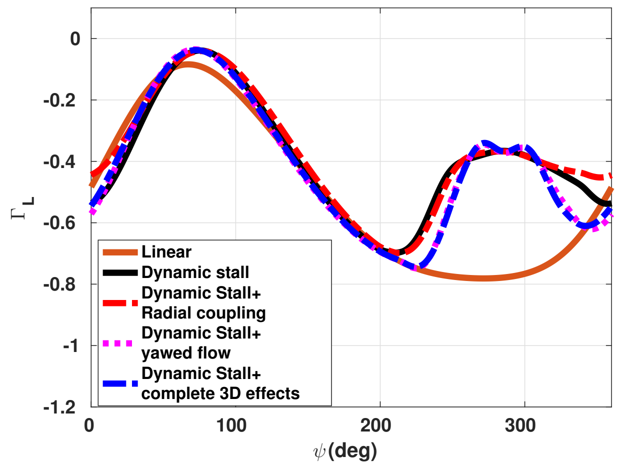

Figure 9: Circulation variation with azimuth angle,$\alpha_S = 12, \theta_0 = 0°, \mu = 0.45, \bar{r} = 0.76$

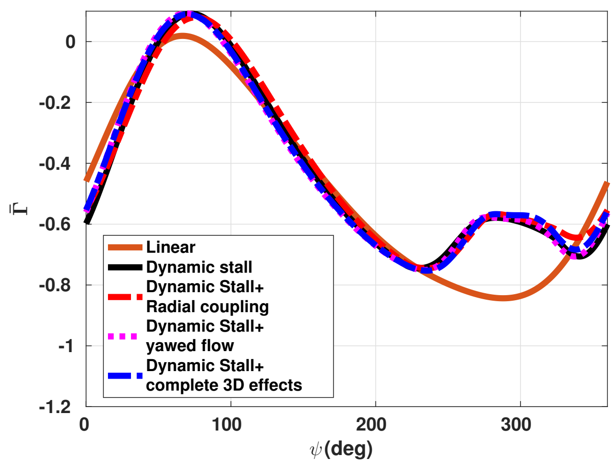

Figure 10: Circulation variation with azimuth angle, $\alpha_S = 12, \theta_0 = 0°, \mu = 0.45, \bar{r} = 0.97$

3.3 Lead-Lag Damping Correlation Results

The main objective of this work is to investigate the effect of 3D dynamic stall on the lead-lag damping correlation. The damping results computed using the ONERA dynamic stall model with yawed flow and radial flow coupling effects using the method described earlier are correlated with experimental data.

Figure 11-12 shows the damping results with uniform inflow model for different α_S. Damping results are shown for all combination of 3D effect components. Radial coupling alone provides a very little improvement from the dynamic stall model without 3D effects and is almost negligible at very high advance ratios. Yawed flow improves the damping results significantly particularly at high advance ratios. Damping results with complete 3D effects are closer to the results with yawed flow effect alone. Overall the dynamic stall model with 3D effects improves the correlation with experimental data at high advance ratios. However the results are not close enough to the experimental results even after including the 3D effects.

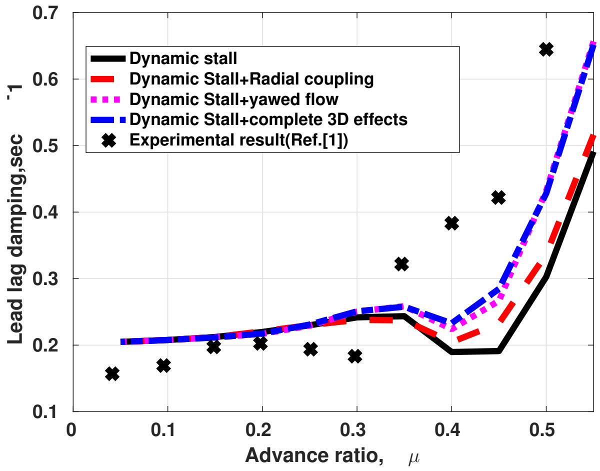

Figure 11: Lead-lag damping correlation results $\theta_0 = 0°\alpha_S = 12°$

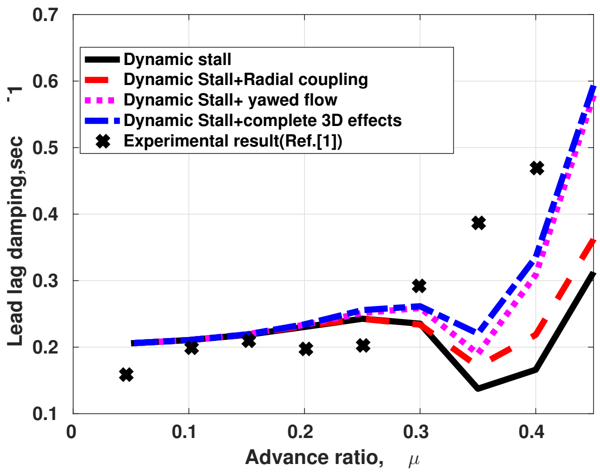

Figure 12: Lead-lag damping correlation results $\theta_0 = 0°\alpha_S = 16°$

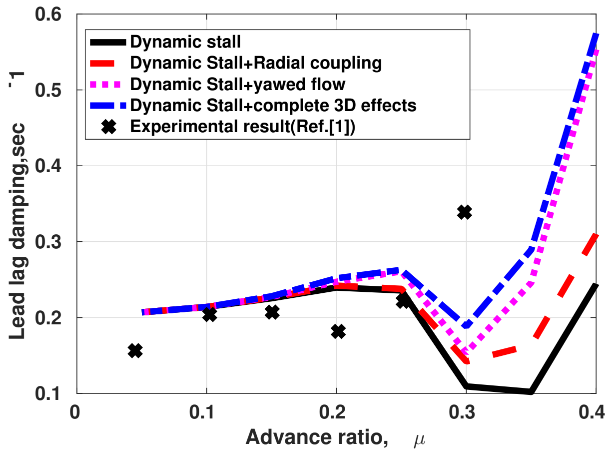

Figure 13: Lead-lag damping correlation results $\theta_0 = 0°\alpha_S = 20°$

3.4 Effect of Dynamic Inflow model in Lead-lag Damping Correlation

In this section the effect of dynamic inflow model in lead lag damping correlation is investigated. Similar to the results with uniform inflow model, the radial coupling alone has little effect on damping results than the yawed flow. Figure 14- 16 shows the damping correlation with dynamic inflow model for different shaft tilt angles. Here the results of dynamic stall model with complete 3D effects are only shown and compared against without dynamic inflow results.

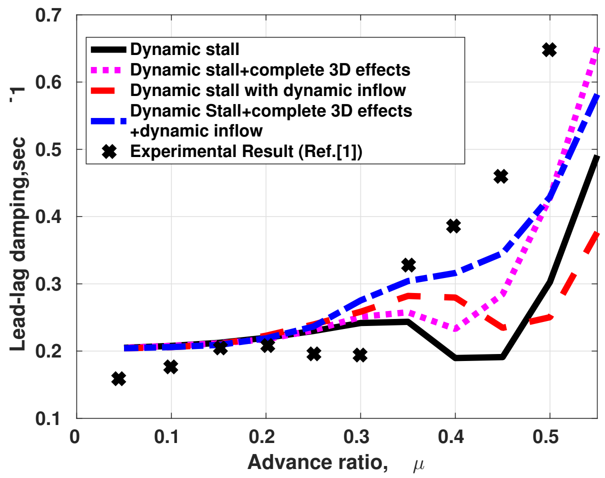

Figure 14: Effect of Dynamic inflow model in Lead-lag damping calculation $\theta_0 = 0°\alpha_S = 12°$

ONERA dynamic stall model with complete 3D effects incorporating dynamic inflow model provides excellent correlation of damping, particularly at high advance ratios. The results however shows a slight over prediction at advance ratios where the 3D effects are negligible suggesting an improved dynamic stall model is required for accurate correlation at all advance ratios.

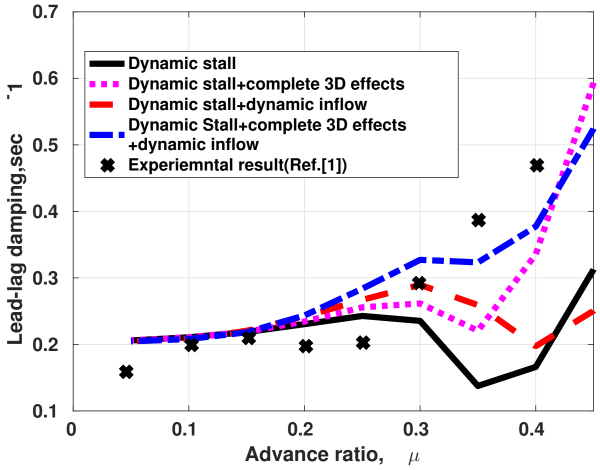

Figure 15: Effect of Dynamic inflow model in Lead-lag damping calculation $\theta_0 = 0° \alpha_S = 16°$

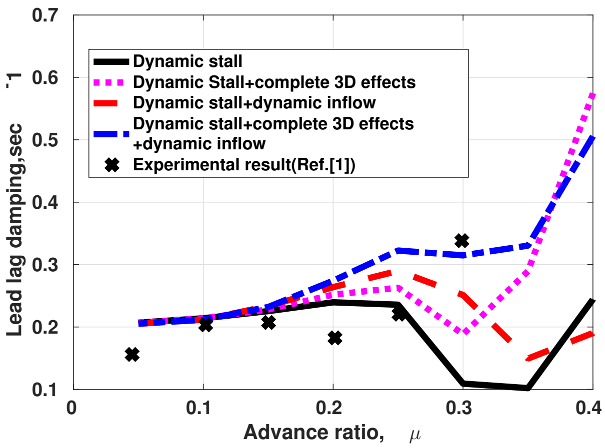

Figure 16: Effect of Dynamic inflow model in Lead-lag damping calculation $\theta_0 = 0° \alpha_S = 20°$

4 CONCLUSION

In this work the Dynamic stall model with 3D effects, yawed flow and radial flow coupling is used to find the lead-lag damping and the results were correlated with available experimental data. Along with damping results equilibrium solution of the rotor were also investigated and discussed. It was observed that the yawed flow effect has major impact on damping results ,particularly at high advance ratios compared to radial coupling effects.It is also evident from the investigation that the 3D effects are more in inboard sections where the dynamic stall and reverse flow effects are more dominant. Peters-He dynamic inflow model proved to be an excellent tool in the lead-damping correlation with yawed flow and radial flow coupling effects.

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