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Engineering Notes

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Improved Dynamic-Stall-Onset Criterion at Low Mach Numbers

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Nomenclature

A = chordwise force
c = chord length
c_c = chordwise force coefficient, A/qc
c_d = drag coefficient, D/qc
c_m = pitching moment coefficient, m/qc^2
c_N = normal force coefficient, N/qc
c_p = pressure coefficient, $\Delta p/q$
D = drag
f = dimensionless separation point in terms of chord length, x/c
L = lift of airfoil section
M = Mach number
m = pitching moment about the axis of the quarter-chord
N = normal force
q = dynamic pressure, $0.5\rho V^2$
r = reduced pitch rate, $\dot{\alpha}c/2V$ (for oscillatory motion of an airfoil, $\kappa\theta_0 \cos\omega t$)
r_0 = reduced pitch rate that delimits the dynamic stall and quasi-steady stall (normally, 0.01)
s = nondimensional time, $2Vt/c$
T_α = time-delay constant for angle of attack
t = time
V = freestream velocity
α = angle of attack or incidence
α' = lagged angle of attack
α_{cr} = critical onset angle (dependent on reduced pitch rate)
α_{ds} = angle of dynamic-stall onset
α_{ds0} = constant critical onset angle
α_{ss} = static stall angle
Δ = a step change in a sampled system
θ_0 = amplitude of airfoil oscillation
k = reduced frequency, $\omega c/2V$
λ = linear fit coefficient for stall-onset incidences
ω = frequency of oscillatory motion of airfoils

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Introduction

DYNAMIC stall is the term used to describe the stalling process of an airfoil, or lifting surface, during unsteady flow conditions. Early work was primarily associated with helicopters [1–6], but more recently, the importance of dynamic stall to wind turbines has been identified, both in terms of their performance and durability. Experimental and numerical investigations on such flows have been widely conducted for several decades [4–11]. The results of these works suggest that dynamic stall is characterized by shedding of a well-concentrated vortex disturbance, provided the reduced frequency, the amplitude, and the maximum incidence are large enough. One important issue associated with the process is the indication of stall onset, which represents the maximum stall-free lift that can be obtained under unsteady conditions (McCroskey et al. [5]). To better understand the complicated phenomenon of dynamic stall, Glasgow University amassed a substantial database pertaining to low-speed dynamic-stall experiments ($M \approx 0.12$) over two decades. It currently contains data from 15 test series (see Sheng et al. [12]). Sheng et al. [13] revisited these data with a view to adjusting the Beddoes stall-onset criterion for the Reynolds and Mach number range of the Glasgow data. They developed a new criterion that lagged the airfoil's incidence until a critical incidence was achieved. This was in contrast to the original method, which lagged the value of c_N until a critical value was obtained using the Evans–Mort [14] correlation.

To achieve this, however, a suitable and consistent indication of stall onset was required. Sheng et al. [13] considered a variety of concepts for the airfoils tested at Glasgow University and concluded that all yielded much the same results. Accordingly, they chose the incidence at which the chordwise force coefficient was a maximum. Sheng et al. applied this criterion to measured data from linear pitch-up motions, ramp-up, and were thus able to extract stall-onset angles for a range of reduced pitch rates.

As illustrated by Sheng et al. [13] and Wilby [15], the typical variation of stall-onset angle for reduced pitch rates larger than a certain value (normally, $r > 0.01$, shown in Fig. 1) is linear. Sheng et al. employed a linear function to fit the data, that is,

$$\alpha_{ds} = \alpha_{ds0} + \lambda r \tag{1}$$

where α_{ds0} and λ can be obtained by fitting Eq. (1) to the experimental data via a least-squares method.

Then Sheng et al. [13] defined a dimensionless time constant T_α as

$$T_\alpha = \frac{\alpha_{ds} - \alpha_{ds0}}{\dot{\alpha}} \frac{2V_\infty}{c} = \frac{\alpha_{ds} - \alpha_{ds0}}{r} = \lambda \tag{2}$$

which effectively represents the time taken for the airfoil's incidence to reach stall onset from the constant critical angle. Table 1 lists both the constant critical onset angle and the time constant for 12 airfoils (the last two columns relate to the lower reduced-pitch-rate criterion, discussed later).

When a lagging of the form

$$\Delta\alpha'(s) = \Delta\alpha(s)[1 - e^{-s/T_\alpha}] \tag{3a}$$

where

$$\begin{cases} \Delta\alpha(s) = \alpha(s) - \alpha(s - \Delta s) \\ \Delta\alpha'(s) = \alpha'(s) - \alpha'(s - \Delta s) \end{cases} \tag{3b}$$

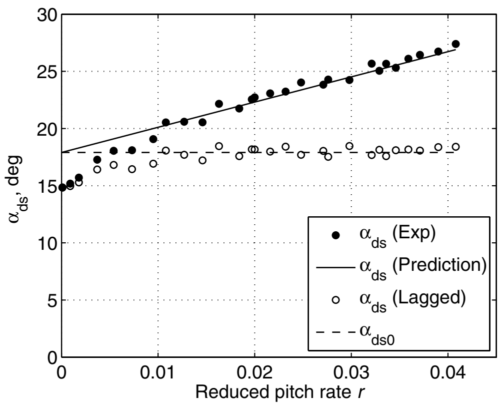


Fig. 1 Experimental and lagged onset angles of dynamic stall for NACA 23012.

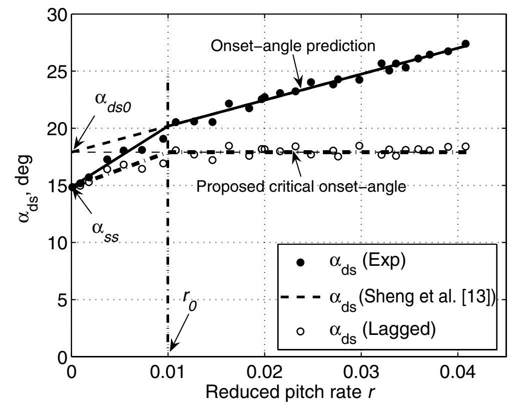


Fig. 2 A schematic graph for the extended model.

is applied, the lagged stall-onset angles (identified by open circles on Fig. 1) are close to the critical angle for reduced pitch rates larger than r_0. Stall onset is said to occur when

$$\alpha' \geq \alpha_{ds0} \tag{4}$$

Referring to Fig. 1, however, it is obvious that below $r = 0.01$, the criterion does not reflect the trend in the measured data. The limiting case is, of course, when $r = 0.0$, for which the criterion suggests that static stall occurs at approximately 18 deg; about 3 deg above the actual value. The failure of the onset criterion to replicate the measured data at low reduced pitch rates is common for all of the airfoils in the Glasgow University database. It is the purpose of the present work to improve the original criterion (Sheng et al. [13]) to the full range of reduced pitch rate.

Improved Stall-Onset Criterion

Figure 2 provides a schematic of the philosophy underlying the development of the new modeling strategy. There it may be seen that the original stall-onset criterion has a constant value for the critical stall-onset angle for the entire range of reduced pitch rate considered. But the experimental data showed that it is correct only for $r \geq r_0$ (an empirical assessment). The new approach is made as follows.

The incidence for ramp-up data can be represented by

$$\alpha(t) = \alpha_0 + \dot{\alpha} t \tag{5}$$

where α_0 is the ramp start angle. In nondimensional form, it could be written as

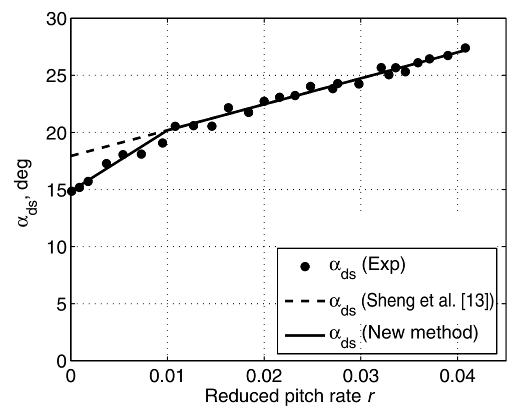
$$\alpha(s) = \alpha_0 + rs \tag{6}$$

and so

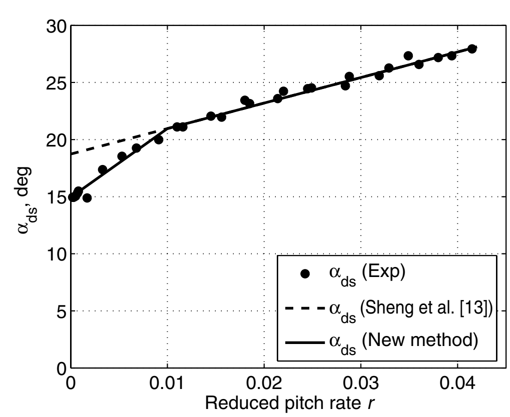
$$\Delta\alpha(s) = r\Delta s \tag{7}$$

Table 1 Dynamic-stall-onset parameters for some airfoils tested at the Glasgow University

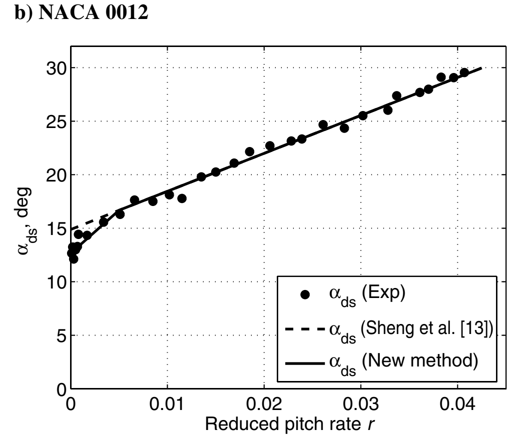
Airfoil	α_{ds0}, deg	T_α	α_{ss}, deg	r_0
NACA 0012	18.73	3.90	14.95	0.01
NACA 0015 ($c = 0.55$ m)	17.81	5.78	14.67	0.01
NACA 0015 ($c = 0.275$ m)	16.79	5.94	14.83	0.01
NACA 0018	17.46	6.22	14.68	0.01
NACA 0021	17.91	6.30	14.33	0.01
NACA 0025	17.22	6.95	13.59	0.01
NACA 23012	17.91	3.97	14.85	0.01
NACA 23012A	17.19	5.11	14.08	0.01
NACA 23012B	18.07	6.14	14.87	0.01
NACA 23012C	18.06	5.59	15.16	0.01
AHAVAW	14.88	6.27	12.66	0.005
GUVA10	15.82	5.70	12.69	0.005



a) NACA 23012



b) NACA 0012



c) AHAVAW

Fig. 3 The improvements of onset-angle predictions, compared with the original method (Sheng et al. [13]).

Equation (7) is substituted into Eq. (3a) and an integration of it yields

$$\alpha'(s) = \alpha(s) - rT_\alpha + rT_\alpha \exp\left(-\frac{s}{T_\alpha}\right) \tag{8}$$

As s becomes large, the last term on the right-hand side diminishes and so may be ignored as being small; hence,

$$\alpha(s) - \alpha'(s) = rT_\alpha \tag{9}$$

For a particular ramp-up test, r is constant and the time delay is assumed to be constant. As such, Eq. (9) suggests that the difference between the angle of attack and the lagged angle is also a constant. That is, the difference between the angle of attack and the lagged angle of attack is proportional to the reduced pitch rate.

At dynamic-stall onset [from Eq. (9)], we have

$$\alpha_{ds} - \alpha_{cr} = rT_\alpha \tag{10}$$

where the difference between the dynamic-stall onset and the critical onset angles is proportional to the reduced pitch rate. From Fig. 2, a piecewise continuous function for α_{cr}, comprising two linear functions, may be obtained, that is,

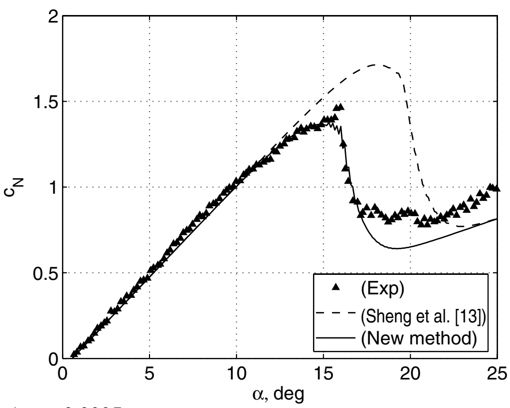
$$\begin{cases} \alpha_{cr} = \alpha_{ds0}, & r \geq r_0 \\ \alpha_{cr} = \alpha_{ss} + (\alpha_{ds0} - \alpha_{ss})\frac{r}{r_0}, & r < r_0 \end{cases} \tag{11}$$

which, together with Eq. (3), is the improved dynamic-stall-onset model for the Glasgow University data. The empirically obtained values of α_{ss} and r_0 are given in Table 1, together with α_{ds0} and T_α.

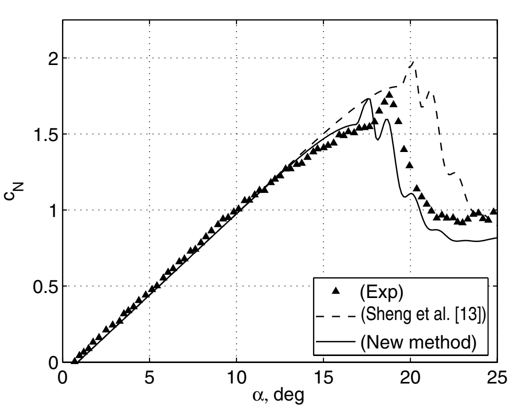
The improved method for indicating dynamic-stall onset is made in the following steps:

1) Calculate the critical stall-onset angle via Eq. (11).
2) Lag the angle of attack via Eq. (3a).
3) Stall onset occurs when $\alpha' \geq \alpha_{cr}$.

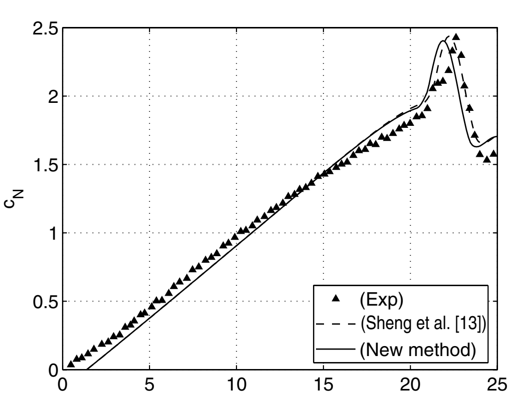
The reconstructions of the stall-onset incidence for the new procedure are illustrated in Fig. 3 for three airfoil ramp-up tests in the Glasgow University database (Galbraith et al. [16]). There it may be observed that the reconstructions are in good agreement with the measured data in all cases. This is also the case for the reconstructions of the normal force coefficients when the new onset criterion is implemented in the Leishman–Beddoes [8] model, as depicted in Fig. 4, compared with the original stall-onset criterion (Sheng et al. [13]) for pitch rates $r \leq r_0$ for the NACA 0012 airfoil section. The inappropriateness of the original criterion is, as may be expected, most evident at the lowest reduced pitch rate. Using the extended criterion, however, the large overshoot in the stall angle for this case has been eliminated. With increasing r and close to r_0 (i.e., 0.0091), the original criterion and the extended version almost converge. It is interesting to note, however, that for this case, the new criterion produces results that are in slightly poorer agreement with the measured data than the original criterion. This is indicative of a



a) $r = 0.0005$

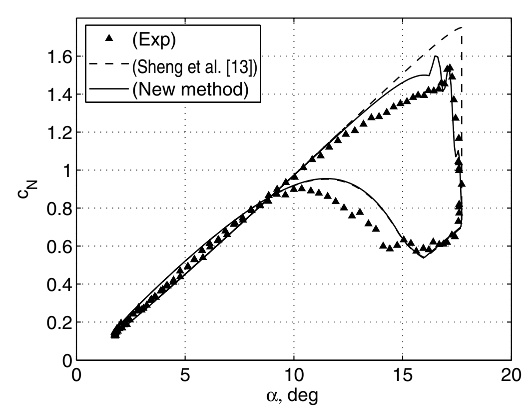


b) $r = 0.0033$

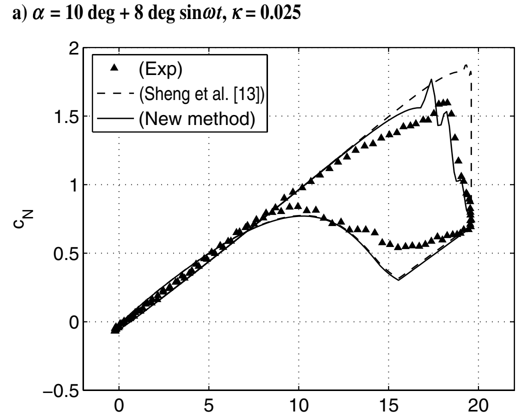


c) $r = 0.0091$

Fig. 4 Normal force reconstructions at low reduced pitch rates for NACA 0012, experimental data taken from Galbraith et al. [16].



a) $\alpha = 10$ deg + 8 deg $\sin\omega t$, $\kappa = 0.025$



b) $\alpha = 10$ deg + 10 deg $\sin\omega t$, $\kappa = 0.025$

Fig. 5 Normal force reconstructions for oscillating tests for NACA 0012, experimental data taken from Galbraith et al. [16].

Table 2 Dynamic-stall-onset angle predictions for oscillating tests (varying θ_0)

k	α_0	θ_0	α_{ds} (exp)	α_{ds} (original)	α_{ds} (new)
0.025	10 deg	8 deg	16.66 deg	N/A	16.22 deg
0.025	10 deg	10 deg	16.93 deg	19.12 deg	16.81 deg

sensitivity in the selection of r_0 and only affects a very small range of reduced pitch rate.

Sinusoidal Motions of Airfoil

To be of true value, the criterion must be applicable to more general motions than simple linear ramps. The applicability of the criterion to sinusoidal pitching motions of the airfoil is now investigated.

To examine the effectiveness of the extended onset criterion for oscillatory motions, it has been compared with test data and the original model [13] for two low-frequency oscillatory cases (Fig. 5).

Compared with the original method (Sheng et al. [13]) from Fig. 5, the new method gives predictions that are closer to the measured data. Table 2 presents the predicted dynamic-stall-onset angle for both of the cases presented for NACA 0012 (experimental data taken from Galbraith et al. [16]). For the 8-deg amplitude case, the original method predicted no dynamic-stall onset, despite the fact that the test data clearly exhibited this event. For the 10-deg amplitude case, the same method did predict dynamic-stall onset, but far too late. In both cases, the new method gave predictions that are much closer to the test data. It should be noted that in these two cases, the time-dependent reduced pitch rate is never larger than r_0, which is why the original method performed so badly.

Conclusions

An improvement to the stall-onset criterion (Sheng et al. [13]) has been developed for low-speed dynamic stall of pitching airfoils. The data used were those of the Glasgow University database of dynamic-stall experiments on smooth-surfaced 2-D airfoils with natural transition and a Reynolds and Mach number of 1.5×10^6 and 0.12, respectively. By introducing a variable critical stall-onset angle, a significant improvement has been made in predicting stall onset at lower reduced pitch rate and lower reduced frequency in ramp and oscillatory motions.

Acknowledgments

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