Prediction of aerodynamic characteristics of HL-CRM using the AMM model

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Motivation

- The k-ε model is widely used in engineering calculations, but not in aeronautical flows
- This reflects impaired predictions for TBLs with separation
- In particular, we see a smaller separation bubble for k-ε than for experiments and SA and SST
- The motivation is to develop the AMM k-ε model with a QCR (AMM-QCRcorner), which predicts wing-body juncture flows
- In APC9, we test the AMM-QCRcorner model against 3D HL-CRM to clarify the prediction on aerodynamic characteristics.

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AMM model (Abe-Mizobuchi-Matsuo 2019) (1/3)

Two-equation eddy viscosity model (low Re k-ε model)

Eddy viscosity approximation

$$\overline{u_i u_j} = \frac{2}{3} k \delta_{ij} - 2\nu_t S_{ij} \qquad \left(S_{ij} \equiv \left(\bar{U}_{i,j} + \bar{U}_{j,i} \right) / 2 \right)$$

Representation of ν_t

$$\nu_t = C_\mu f_\mu k^2 / \varepsilon$$

k equation

$$\frac{\partial k}{\partial t} + \bar{U}_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left\{ \left(\nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right\} + P_k - \varepsilon$$

ε equation

$$\frac{\partial \varepsilon}{\partial t} + \bar{U}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left\{ \left(\nu + \frac{\nu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right\} + \frac{\varepsilon}{k} \left(C_{\varepsilon 1} P_k - C_{\varepsilon 2} f_\varepsilon \varepsilon \right)$$

Model functions

$$f_\mu = \left\{ 1 - \exp\left(-\frac{R_y}{A} \right) \right\} \left[1 + \frac{5}{R_t^{3/4}} \exp\left\{ -\left(\frac{R_t}{200} \right)^2 \right\} \right] \quad (A = 120) \qquad f_\varepsilon = \left\{ 1 - \exp\left(-\frac{R_y}{B} \right) \right\} \left[1 - \frac{2}{9} \exp\left\{ -\left(\frac{R_t}{6} \right)^2 \right\} \right] \quad (B = 12)$$

$$\left(R_t = k^2 / \nu\varepsilon \qquad R_y = \sqrt{k} y / \nu \right)$$

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AMM model (Abe-Mizobuchi-Matsuo 2019) (2/3)

Model constants modification

(2022 TSFP; 2022 NASA Turbulence model Symp.; AIAA J Submitted)

Model constants	C_μ	σ_k	σ_ε	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$
AMM	0.09	$1.1/f_{sig}$	$1.25/f_{sig}$	1.5	1.9

$$\left(f_{sig} = 1 + 6\left(-\exp\left(R_y / 20 \right)^2 \right) \qquad R_y = \sqrt{k} y / \nu \right)$$

Eddy viscosity modification (2022 TSFP)

$$\nu_t = \frac{\rho C_\mu f_\mu k T_\mu}{\left(1 + C_{S\Omega} \left[\left(S_{ij}^2 - \Omega_{ij}^2 \right) (k/\varepsilon)^2 \right]^2 \right)^{1/2}}$$

$$\left(T_\mu = \min\left(\frac{k}{\varepsilon}, \frac{0.6}{\sqrt{6}} \frac{1}{C_\mu S_{ij}^2} \right) \quad C_{S\Omega} = 1 \qquad S_{ij} = \frac{1}{2}\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right), \ \Omega_{ij} = \frac{1}{2}\left(\frac{\partial \bar{U}_i}{\partial x_j} - \frac{\partial \bar{U}_j}{\partial x_i} \right) \right)$$

- ν_t is modified by incorporating a parameter $S_{ij}^2 - \Omega_{ij}^2$, representing the acceleration and retardation of the mean flow, into the turbulence time scale T_μ using the augmented time scale procedure by Yoshizawa et al. (2006).
- This is done to avoid the large magnitude of ν_t in the trailing edge where the adverse pressure gradient is large.

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AMM model (Abe-Mizobuchi-Matsuo 2019) (3/3)

Two-equation eddy viscosity model (low Re k-ε model)

Improved Quadratic Constitutive Relation (QCRcorner) (2023 TSFP)

We consider the non-zero value of the mean streamwise vorticity in a corner flow where the Reynolds stress anisotropy plays a crucial role (Bradshaw 1987).

In QCRcorner, a ΩΩ term is added to the original AMM-QCR, i.e.

$$-\overline{u_i u_j} = -\frac{2}{3}k\delta_{ij} + 2\nu_t S_{ij} - C_1\frac{k}{\varepsilon}\nu_t\left[\Omega_{ik}S_{jk} + \Omega_{jk}S_{ik}\right] - C_2\frac{k}{\varepsilon}\nu_t\left[S_{ik}S_{kj} - \frac{1}{3}S_{mn}S_{mn}\delta_{ij}\right]$$

$$-C_3\frac{k}{\varepsilon}\nu_t\left[\Omega_{ik}\Omega_{kj} + \frac{1}{3}\Omega_{mn}\Omega_{mn}\delta_{ij}\right] \qquad C_1 = 0.6, C_2 = 0.2, C_3 = -0.3$$

C_1, C_2, C_3 have been determined using DNS data in the channel and square duct.

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APC9 Case 2

Geometry	3D CRM-HL
Flap deflection (inboard/outboard)	40deg / 37deg
Re_c	5.49×10^6
T_{ref}	521R
AoA	5.98, 15.48, 17.98, 19.98 deg
Grid	HLPW4 105T-ANSA-Unstructured-Yplus1
Grid Level	B (Node number 120,515,486) (Cell number 155,749,703)

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Solver

The flow solver used in this work is FaSTAR developed by JAXA (Hashimoto et al. 2012 AIAA paper), which is an unstructured-grid compressible flow solver with the second-order accuracy. In the present study, the inviscid flux scheme HLLEW (Obayashi and Guruswamy 1995 AIAA J.) is used for the convective terms. The numerical flux has been calculated at a cell vertex.

Turbulence model

AMM-QCRcorner, AMM
(Turbulence intensity 0.6% , Viscous ratio 10)

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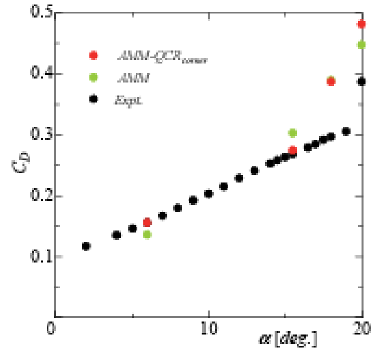
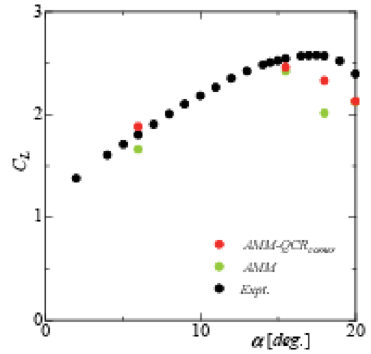
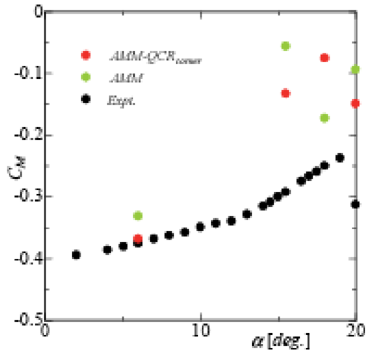
Aerodynamic coefficients



Use of QCR is useful for improving aerodynamic coefficients





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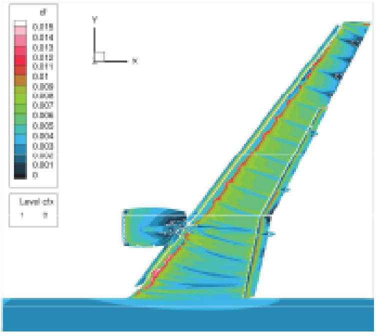
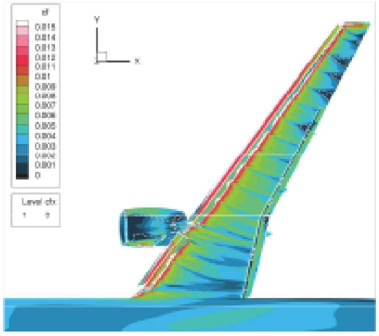
Surface Cf contours (AMM-QCRcorner)

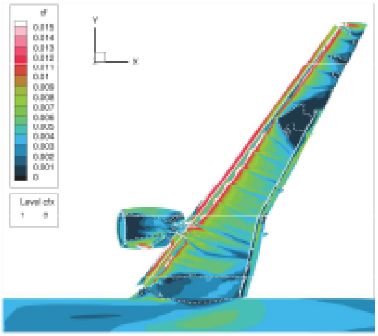
AoA=5.98deg



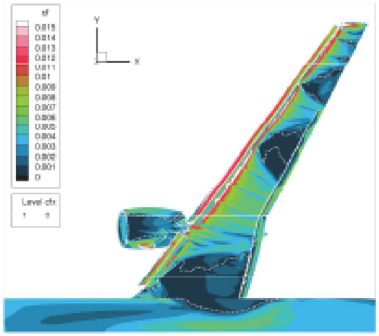
AoA=15.48deg



AoA=17.98deg



AoA=19.98deg



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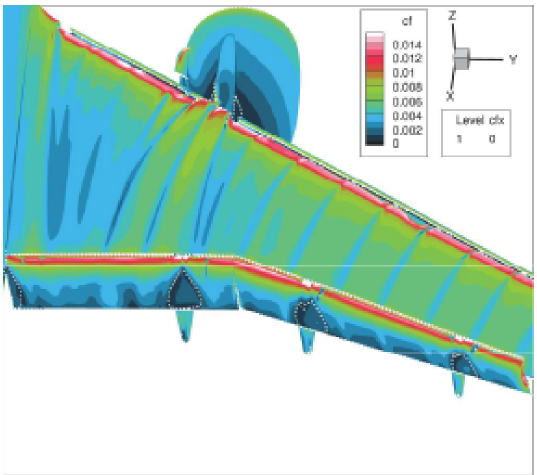
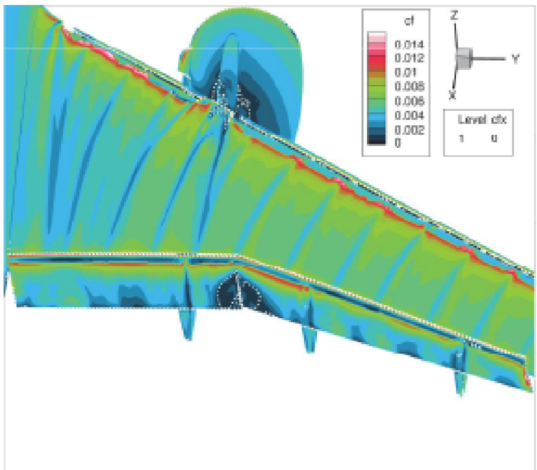
Surface Cf contours

AoA=5.98deg

AMM



AMM-QCRcorner



Use of QCR yields an increased positive Cf over the wing

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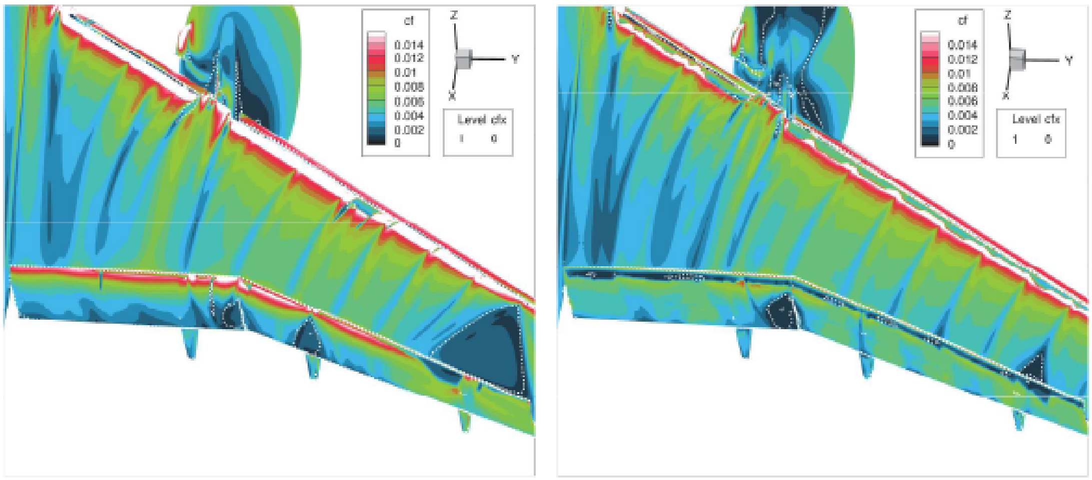
Surface Cf contours

AoA=15.48deg

AMM AMM-QCRcorner



Use of QCR also avoids a large separated region

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Summary

- AMM-QCRcorner predicts aerodynamic coefficients reasonably for AoA = 5.98 and 15.48 deg , but not for AoA= 17.98 and 19.98 deg. C_{Lmax} is not well predicted.
- QCR is useful for improving aerodynamic characteristics at each AoA. Use of QCR yields an increased positive C_f region over the wing and also avoids a large separated region.
- At large AoA, AMM-QCRcorner predicts large separated regions not only in the mid span of the wing, but also near the wing-body juncture, highlighting that further improvement is required for the prediction of separated flow.

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