3rd Aerodynamic Prediction Challenge
28. Jun. 2017 @ National Olympics Memorial Youth Center, Tokyo

CflowによるNASA-CRMの JAXA及びETW風試条件での解析

CFD Result of NASA-CRM using Cflow with Wind Tunnel Test Conditions at JAXA and ETW

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KHI proprietary

Intruduction　Validation Procedure　Wing Deformation Effect Correction　Computational Methods　Result　Summary

Introduction of "*Cflow*"

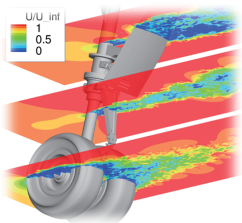
Kawasaki original CFD tool

Cflow = Grid Generator + Flow Solver

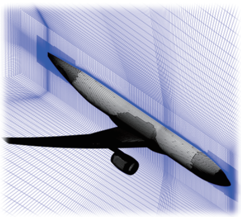
Cartesian based AMR
＋layered grid

highly complicated　unsteady　large-scale

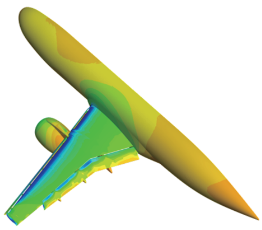
■ Cflow has been validated in various workshops.



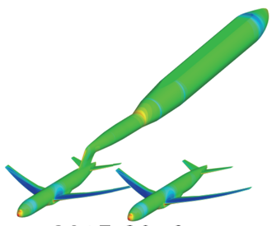
2010-2016
BANC I-IV



2016
DPW6



2017
HiLift-PW3



2015-2016
APC-I, II

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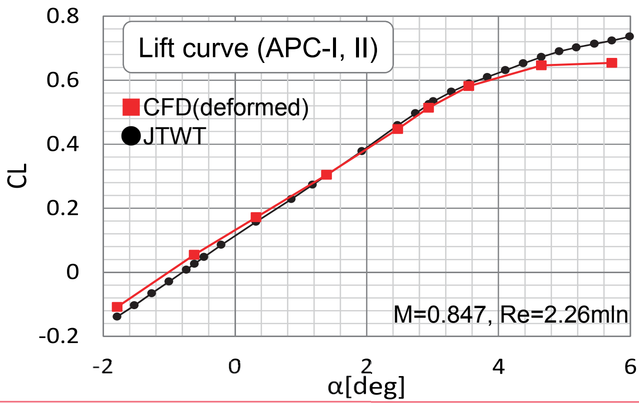
Background

APC-I, II

- **Lift curve slope** obtained by CFD did not agree with **JTWT**[*1] test despite taking wing deformation into account.



JTWT
　WIC* applied
　SIC* applied (CFD based)
CFD
　No tunnel wall
　No sting support

*1 WIC : Wall Interference Correction
*2 SIC : Sting Interference Correction

APC-III (Sub.2)

- Results of **ETW**[*2] test and CFD are compared here.

*1 JTWT : JAXA Transonic Wind Tunnel　*2 ETW : European Transonic Wind tunnel

Wind Tunnel Test Conditions

APC-I, II　　This presentation

Wind Tunnel	JTWT	ETW*	
Re (x 10⁶)	**2.26**	**5**	**30**
Mach	0.847	0.85	
P0[kPa]	120	191	303
Q[kPa]	**37.7**	**60.6**	**95.5**
Model Size (b/2) [mm]	**634.635 (80% of ETW model)**	**793.242**	
Case No.	4222	153	233

- **ETW test conditions are different from JTWT test.**
  - Reynolds number ⇨ Reynolds number effect
    The same Re number was applied to CFD.
  - Dynamic Pressure (Q)
  - Model Size
  ⇨ **Wing deformation effect**
    Deformed wing geometries were not available for arbitrary AoA.

* ETW test data : http://www.eswirp.eu/ETW-TNA-Dissemination.html

CFD Validation Procedure

- **Validation methods**
  - Deformed wing geometry for ETW test case was not available for arbitrary angles of attack.
  - CFD was conducted with **non-deformed geometry**.
  - **Lift curve for deformed wing was estimated** by following steps.
    - **(1) Estimate displacement** at wing tip (wtip) in the ETW test using JTWT test results.
    - **(2) Estimate ΔCL** ($CL_{deformed}$ − $CL_{non\text{-}deformed}$) using relationship of ΔCL .vs. wtip obtained by CFD under the JTWT test condition.
    - **(3) Lift curve for deformed wing was estimated** by correcting wing deformation effect using the ΔCL values calculated above.
  - **CFD results were compared with ETW test under the same condition (deformed wing, w/o sting).**

Estimation Method of Wing Tip Displacement

- **Wing tip displacement** was estimated by **Bernoulli-Euler beam theory** assuming uniform load.

$$w_{tip} \propto \frac{CL * q}{EI}$$

Scaled by total CL at wind tunnel test (CL)

Scaled by dynamic pressure at wind tunnel test. (q)

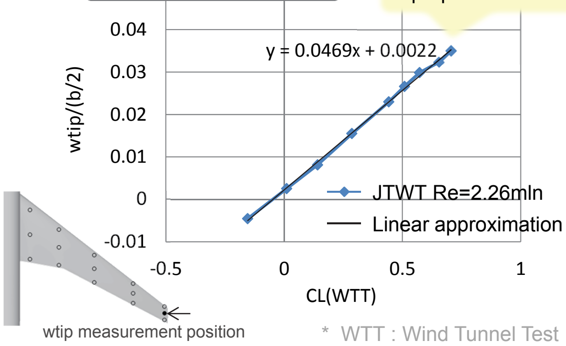
Bending stiffness (EI) is scaled by 4th power of model span.

- Young's modulus (E) was assumed to be the same in all models.
- Second moment of area (I) has dimension of 4th power of length.

$$I_x = \int_A y^2 dA$$

wtip .vs. CL (JTWT)

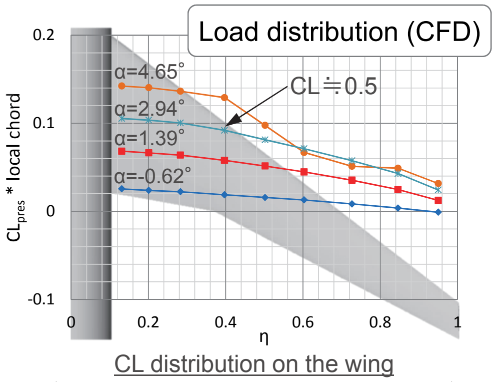
Wing tip displacement (wtip) is proportional to total CL.



wtip measurement position

* WTT : Wind Tunnel Test

Load distribution (CFD)



CL distribution on the wing
（APC-II, deformed wing, Re=2.26mln, Cflow）

(1) Estimation of Wing Tip Displacement

- Graph below shows CL(wind tunnel test) versus wing tip displacement (wtip).

(1) Estimate wtip

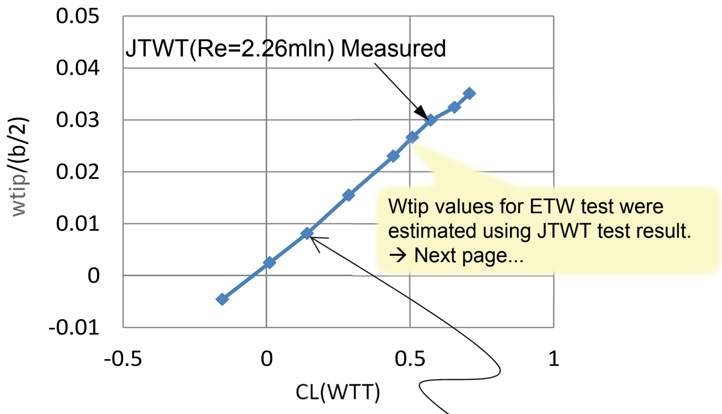
Wing tip displacement (wtip)

(2) Estimate ΔCL

$$\Delta CL = f(w_{tip}) * \frac{CL\alpha^{ETW}_{non-deformed}}{CL\alpha^{JTWT}_{non-deformed}}$$

(3) Calculate $CL_{deformed}$

$CL_{deformed} = CL_{non-deformed} + \Delta CL$



$$\left(\frac{wtip}{b/2}\right)_{ETW} = \frac{\frac{CL_{ETW}}{CL_{JTWT}} * \frac{q_{ETW}}{q_{JTWT}}}{\left(\frac{b_{ETW}}{b_{JTWT}}\right)^4} * \left(\frac{wtip}{b/2}\right)_{JTWT} \quad @each\ AoA$$

Intruduction | Validation Procedure | Wing Deformation Effect Correction | Computational Methods | Result | Summary

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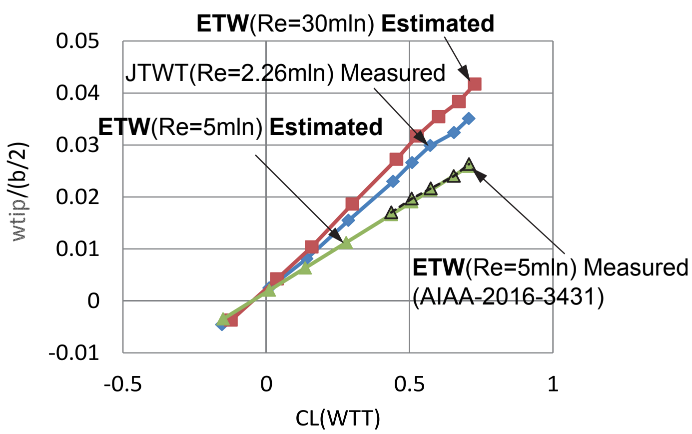
$CL_{deformed} = CL_{non-deformed} + \Delta CL$



Bending stiffness (EI) was scaled by 0.9 for ETW model as to estimated wtip agreed with measured wtip in Re=5mln case..

(2) Estimation of ΔCL

■ Method of estimating **ΔCL** (=$CL_{deformed}$ − $CL_{non\text{-}deformed}$) for CFD results with the ETW test conditions.

(1) Estimate wtip

Wing tip displacement (wtip)

(2) Estimate ΔCL

Lift curve slope at each AoA in CFD.

$$\Delta CL = f(w_{tip}) * \frac{CL\alpha^{ETW}_{non-deformed}}{CL\alpha^{JTWT}_{non-deformed}}$$

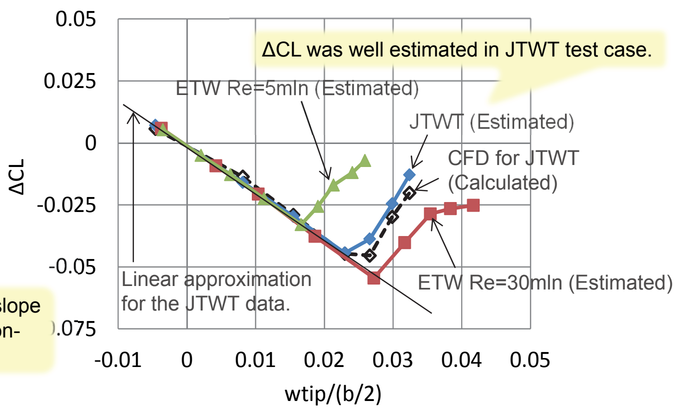
Linear function.

Averaged lift curve slope at linear region in non-deformed CFD.

(3) Calculate $CL_{deformed}$

$CL_{deformed}=CL_{non\text{-}deformed}+\Delta CL$

Estimated ΔCL



(3) Calculation of $CL_{deformed}$

■ Method of estimating **ΔCL** (=$CL_{deformed}$ − $CL_{non\text{-}deformed}$) for CFD results with the ETW test conditions.

(1) Estimate wtip

Wing tip displacement (wtip)

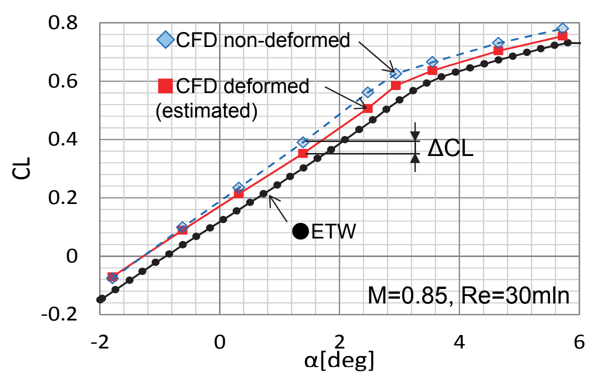
(2) Estimate ΔCL

$$\Delta CL = f(w_{tip}) * \frac{CL\alpha^{ETW}_{non-deformed}}{CL\alpha^{JTWT}_{non-deformed}}$$

(3) Calculate $CL_{deformed}$

$CL_{deformed}=CL_{non\text{-}deformed}+\Delta CL$

Estimated Lift Curve



Both effects of wing twist and bending were included in the ΔCL because ΔCL was obtained from CFD results with deformed* and non-deformed geometry.

* Wing twist and bending were reflected to the deformed geometry.

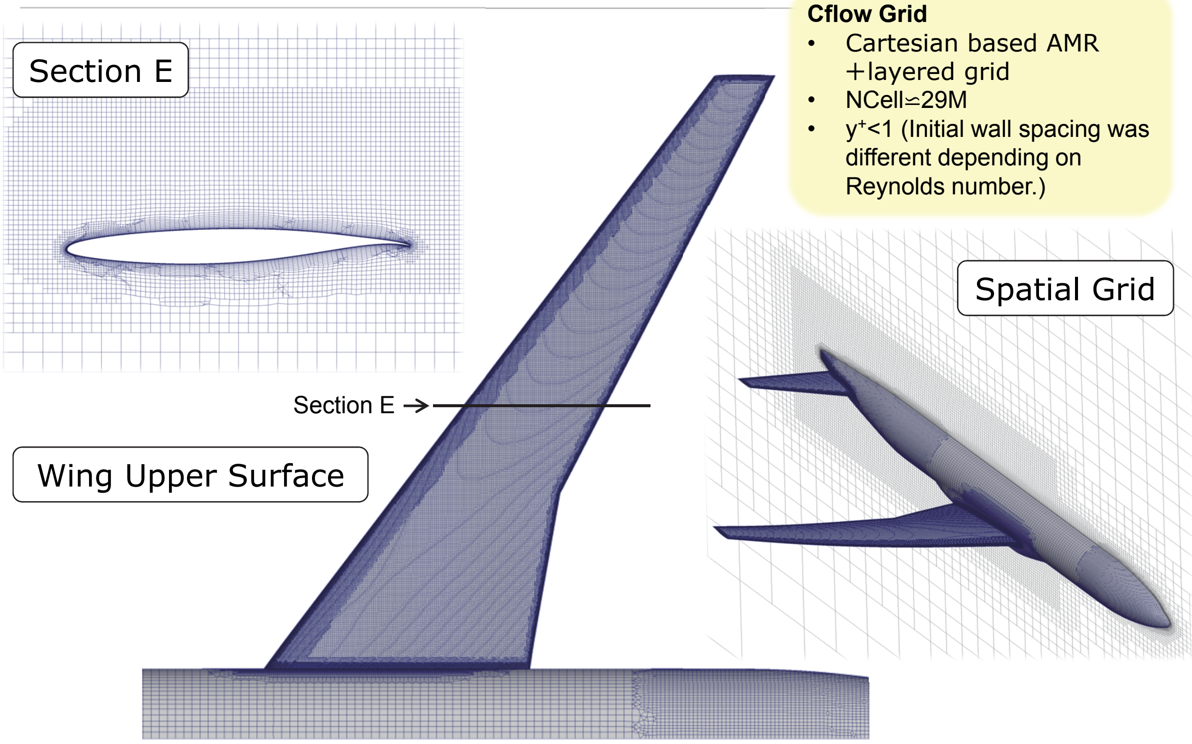
Computational Methods

- Cflow solver methods are summarized in the table below.
  - The same methods were employed in APC-I and II.

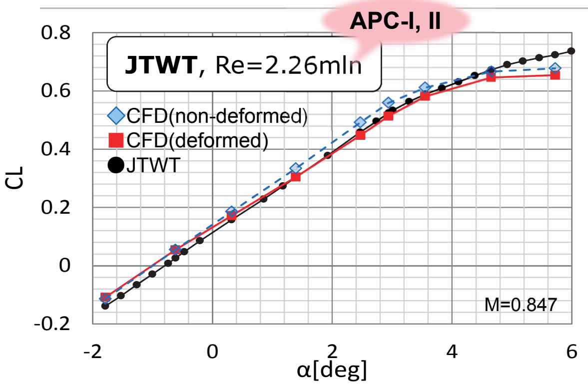
	Solver methods
Gverning Equations	**RANS** (Reynolds Averaged Navier-Stokes) equations
Spatial Discretization	Cell-centerd finite volume method with 2nd-order accurate reconstruction based on MUSCL
Inviscid Flux	SLAU (Simple Low dissipation AUSM) scheme
Viscous Flux	2nd-order accurate central difference
Time Integration	MFGS (Matrix Free Gauss Seidel) implicit method with local time stepping
Turbulence Model	**SA-noft2** (fully turbulent)

Computational Grid

Cflow Grid
- Cartesian based AMR +layered grid
- NCell≒29M
- $y^+<1$ (Initial wall spacing was different depending on Reynolds number.)



Result – Lift Curve

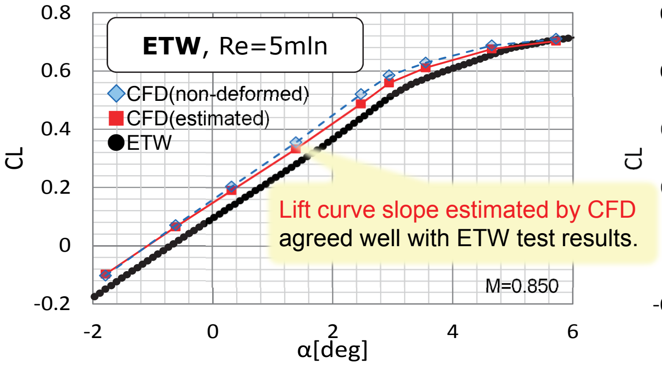


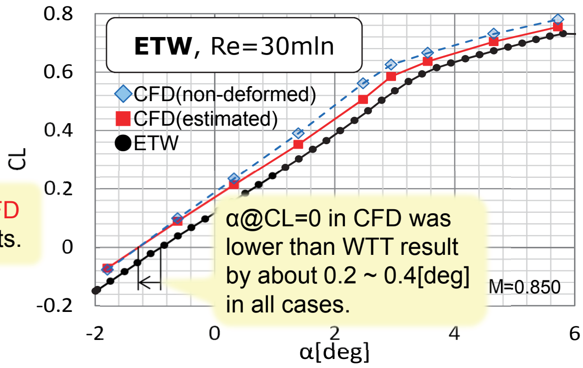
Data Correction

JTWT
- WIC applied
- SIC applied (CFD based)

ETW
- WIC applied
- SIC applied

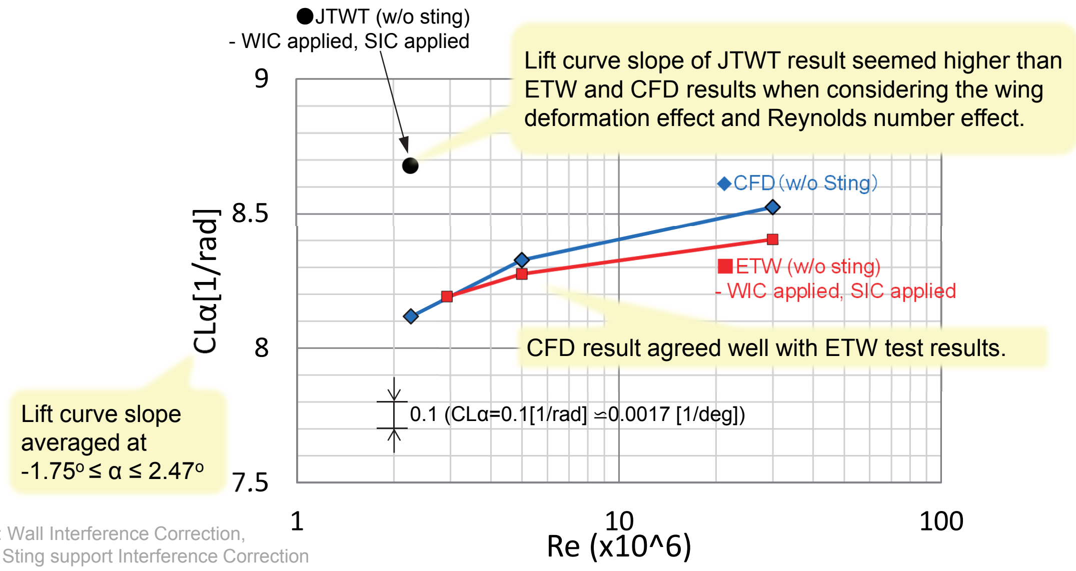
CFD
- No tunnel wall
- No sting support





Lift Curve Slope

- Graph below shows **lift curve slope** versus **Reynolds number**.
  - **Wing deformation effect was eliminated** in all data.



WIC : Wall Interference Correction,
SIC : Sting support Interference Correction

Summary

- **Lift curves** were compared in CFD and ETW results.
  - Wing deformation effect on the lift curve was corrected using CFD result with the JTWT test condition.
  - Lift curve slope obtained by CFD agreed well with ETW test results when wing deformation effect was corrected, while not agreed with JTWT test.
  - Lift curve slope obtained in JTWT test seemed higher than ETW test result when considering the effects of wing deformation and Reynolds number.
    - Effect of porous ratio of the wind tunnel wall?
  - α@CL=0 obtained by CFD was lower than WTT by about 0.2 - 0.4[deg] in all cases.
    - Turbulence model effect?

Appendix

Results of Discussion with JAXA after APC-III

Abstract

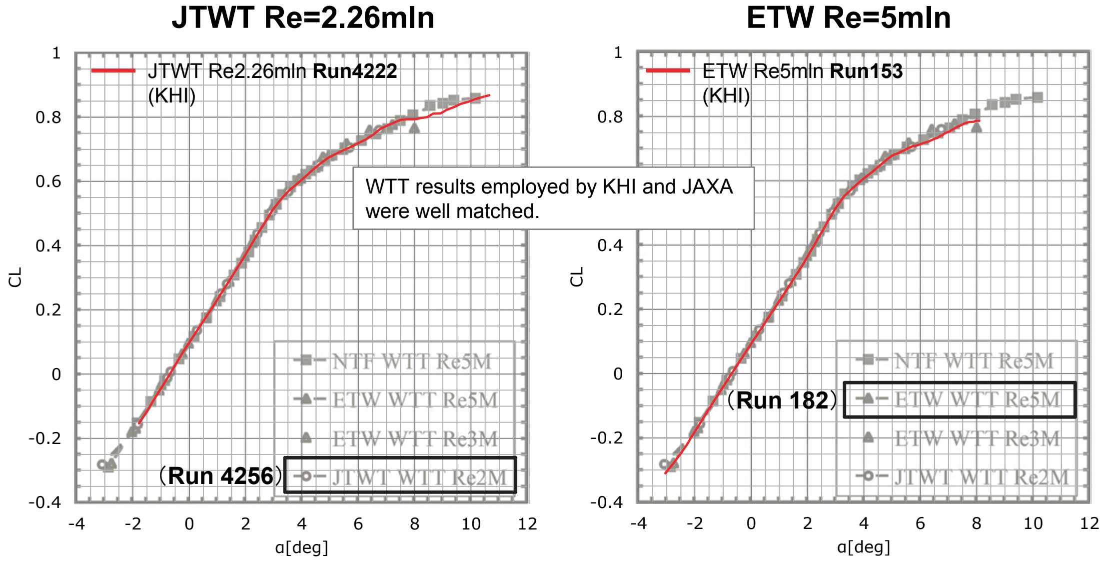
KHI and JAXA discussed the wing deformation correction results of lift curve and its slope. At first, wing deformation effect correction results of KHI and JAXA were compared. JAXA results were quoted from [1]. After that, lift curve slope was calculated using JAXA corrected data. As a result, KHI results and JAXA results were well agreed.

[1] K. Yasue, M. Ueno, "Model Deformation Corrections of NASA Common Research Model Using Computational Fluid Dynamics," Journal of Aircraft, Vol. 53, No. 4, (2016).

WTT Result w/o WDC*

* Wing Deformation effect Correction

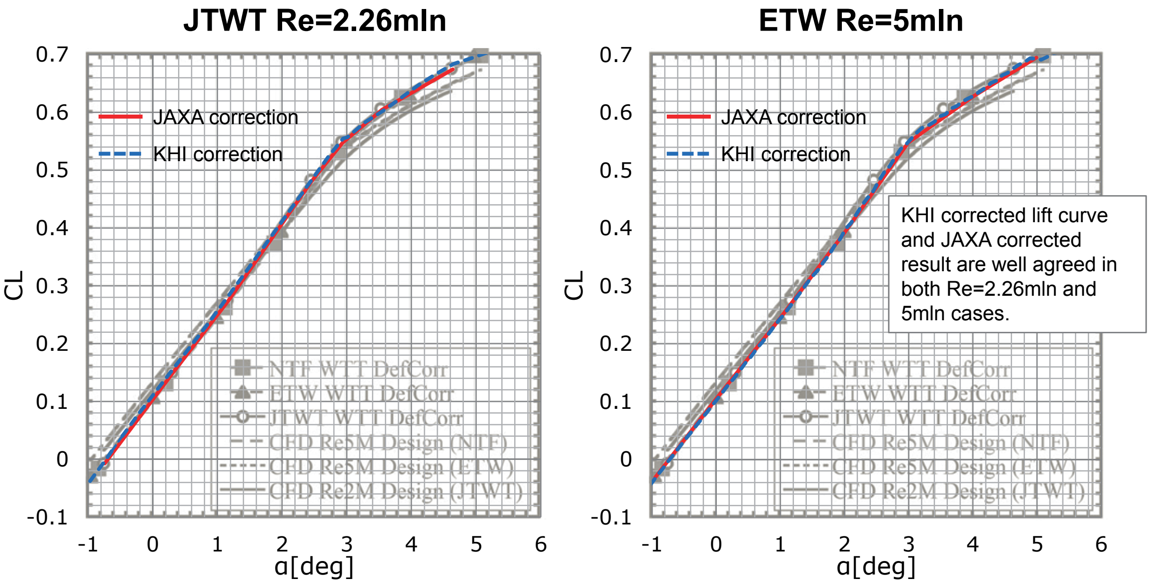
WTT results employed by KHI and JAXA[1] are different run. So WTT results without wing deformation effect are compared before discussing WDC.



JAXA data : [1] Fig. 4 a)　　JAXA data : [1] Fig. 4 a)

WTT results w/ WDC (KHI .vs. JAXA method)

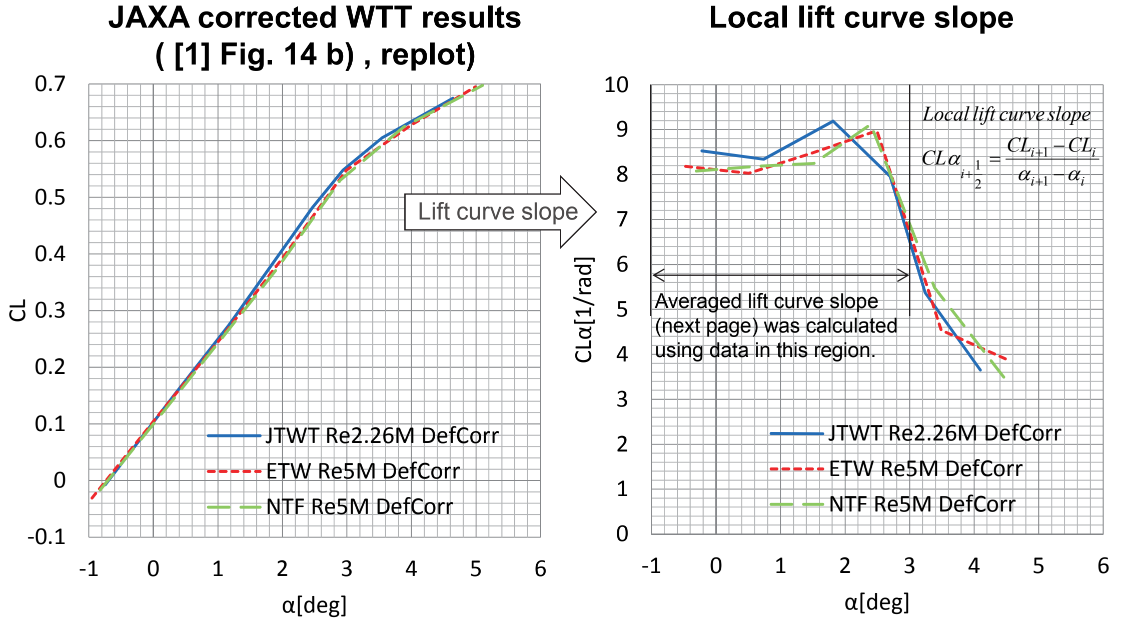
WTT results corrected by KHI and JAXA are compared. JAXA correction used CFD to obtain ΔCL between deformed and non-deformed configuration.



JAXA data : [1] Fig. 14 b)　　JAXA data : [1] Fig. 14 b)

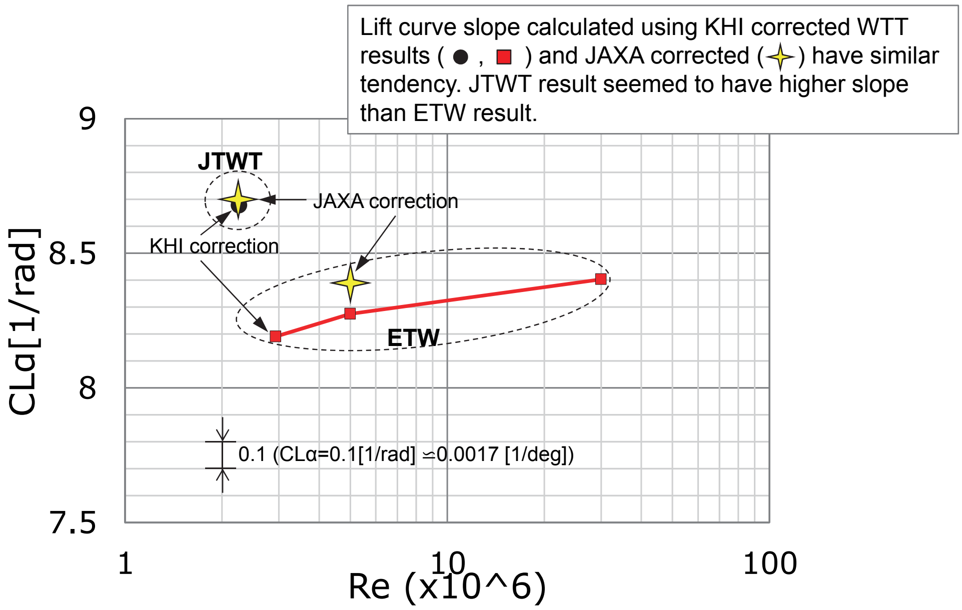
Lift Curve Slope of JAXA Corrected WTT Results

Graph below shows lift curve ([1] Fig. 14 b)) and local lift curve slope calculated from the lift curve. Local lift curve slope of JTWT case seems higher than ETW Re5M case in α<2[deg].



Lift Curve Slope

✦ Lift curve slope calculated by least-squares method using JAXA corrected WTT results.



Acknowledgement

Authors would like to show special thanks to JAXA who had discussions together after APC-III and provided us the digital data of the paper for comparing the wing deformation effect correction on the lift curve.

There may be some issues both in CFD and wind tunnel test. Discussing such issues in the future APC will contribute to improve CFD and wind tunnel test technology.

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