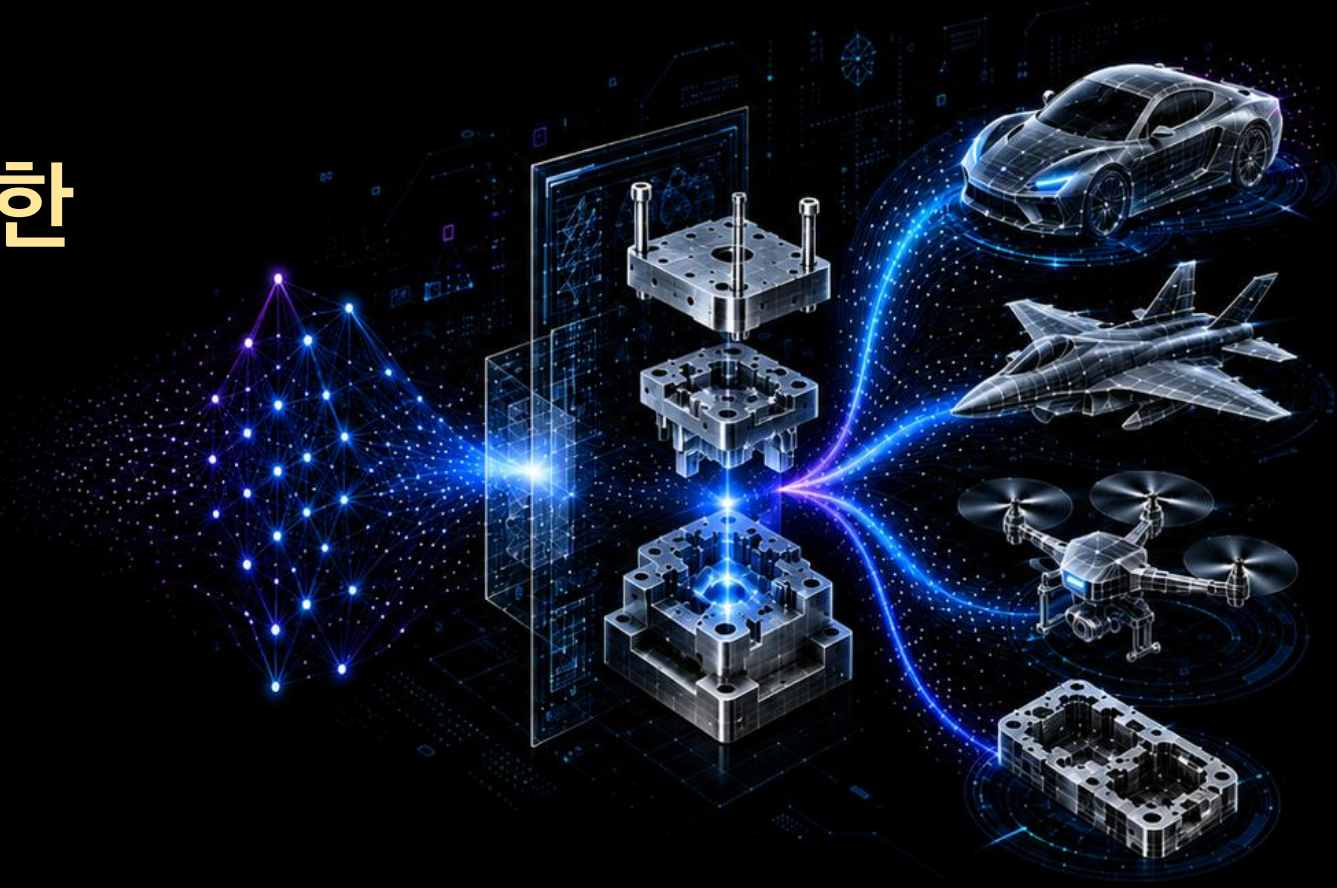
대한기계학회 2026년 학술대회

자율 Remeshing을 위한 CFD 메싱 에이전트



정 승 한, 최 준 석
(지도교수: 양선웅)

한양대학교 ERICA 기계공학과

Intelligent Design for Engineering Applications Lab

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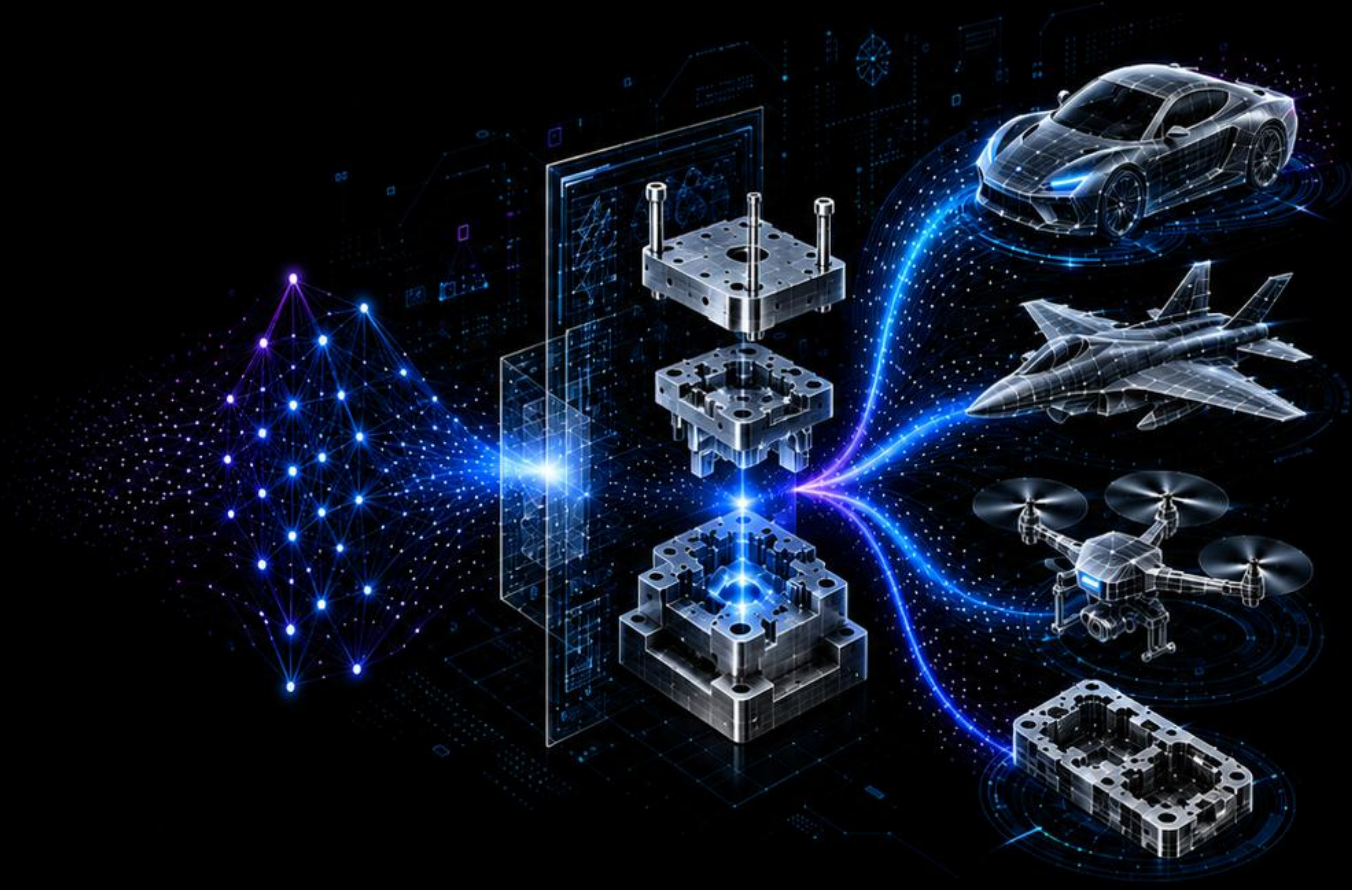
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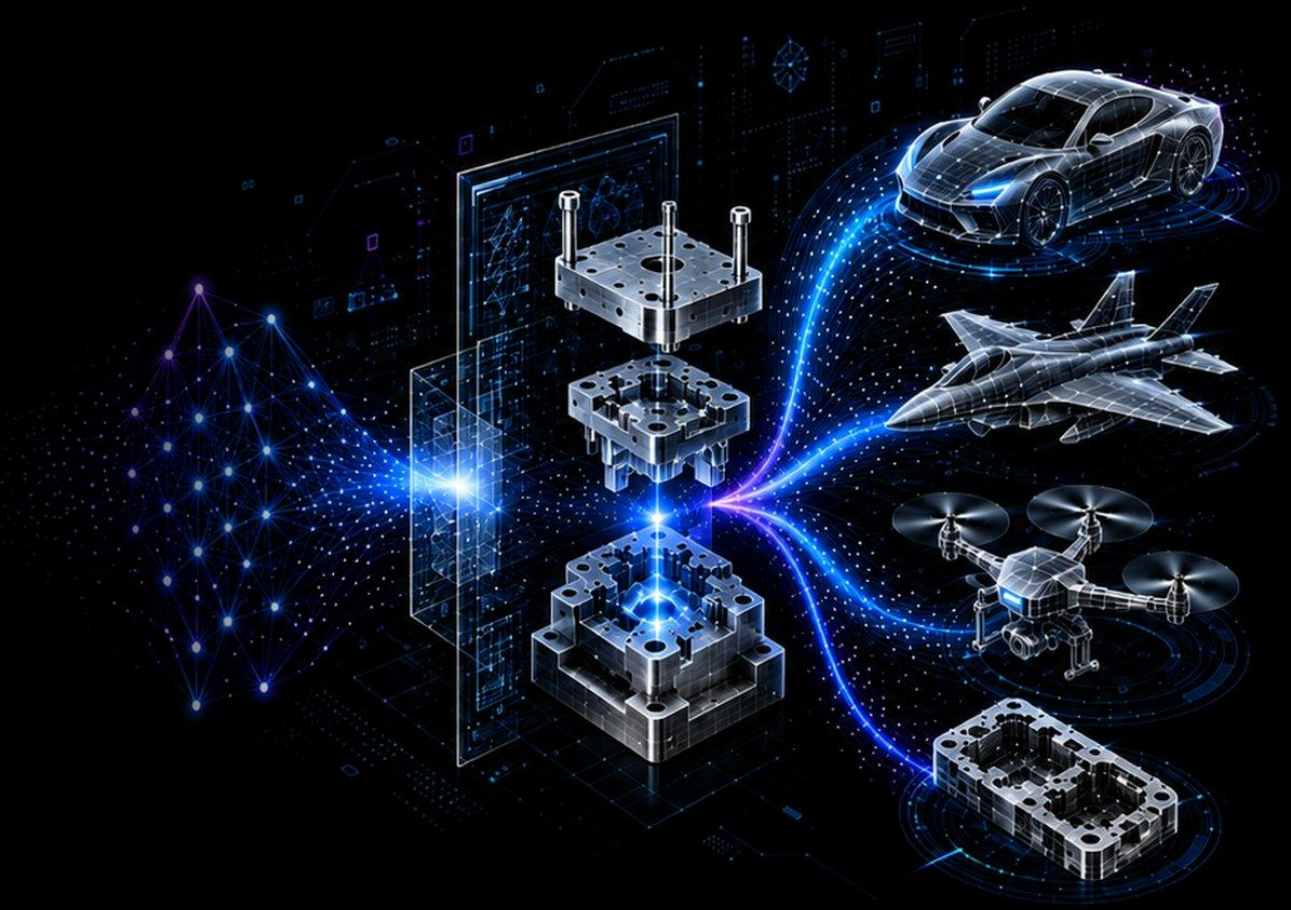


Intelligent Design for Engineering Applications Lab

PART

I

Introduction



- Meshing agent의 필요성
- Local LLM의 필요성
- Overall framework

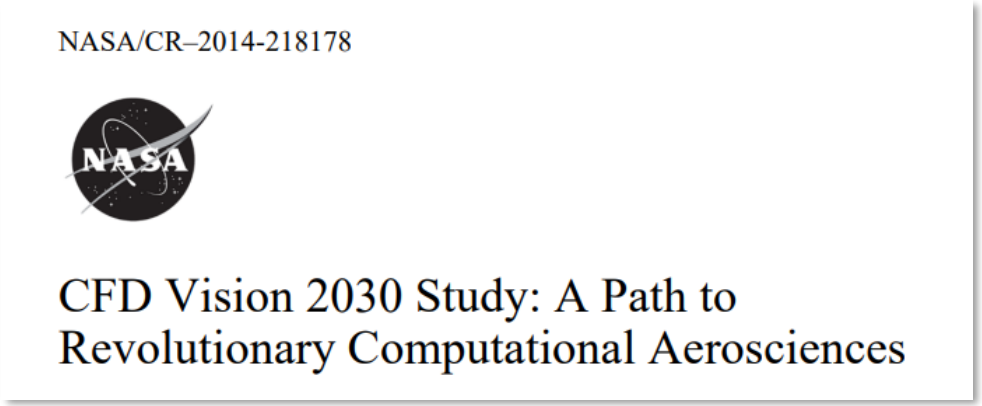
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Part 4 Conclusion

Meshing agent의 필요성

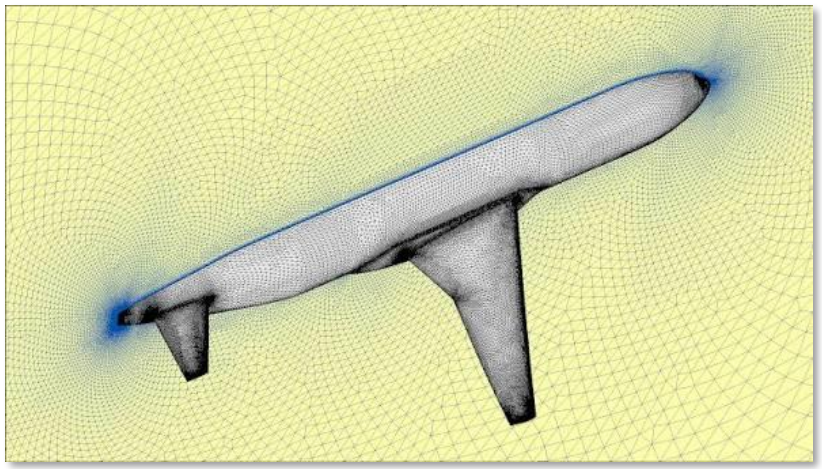
- NASA에서 발표한 CFD Vision 2030


NASA/CR–2014-218178

NASA

CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences

▲ CFD Vision 2030 study



▲ NASA CRM CFD mesh

- NASA CFD Vision2030는 CFD 관련 7가지 문제를 제시
  - ✓ 4번째 문제점에서 Mesh generation & Adaptivity 에 대해 언급함
- NASA에서는 meshing 관련하여 다음과 같은 문제를 구체적으로 지적
  - ✓ 사람의 반복적인 개입 필요 : 격자 생성의 낮은 robustness(강건성)[1]
  - ✓ 자동 적응격자의 필요성 : 목표 해석 정확도를 만족하도록 격자를 스스로 조정하는 기술 필요[1]

[1] Slotnick, J., Khodadoust, A., Alonso, J., Darmofal, D., Gropp, W., Lurie, E., & Mavriplis, D. (2014). *CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences*. NASA Contractor Report NASA/CR-2014-218178.

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Meshing agent의 필요성

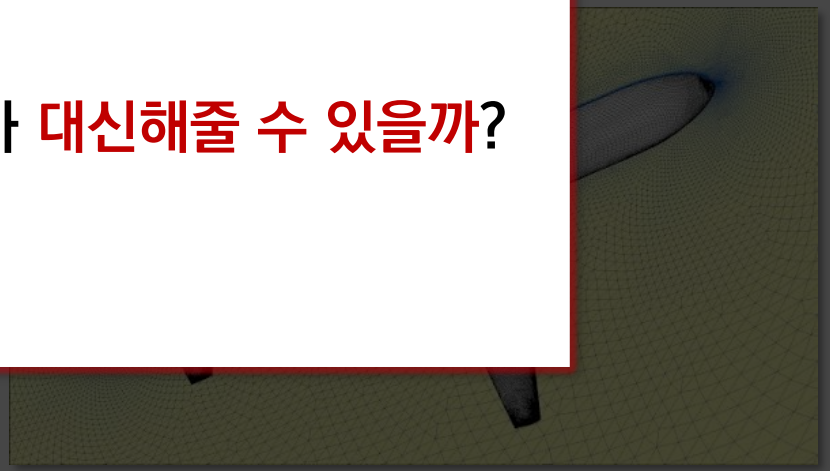
- NASA에서 발표한 CFD Vision 2030

- Mesh generation and adaptivity continue to be significant bottlenecks in the CFD workflow, and very little government investment has been targeted in these areas.

the dominant
cerns about the

Research Question

Initial meshing 부터 CFD remeshing까지 agent가 대신해줄 수 있을까?



- N
  - ✓ 4번째 문제점에서 Mesh generation & Adaptivity 에 대해 언급함
- NASA에서는 meshing 관련하여 다음과 같은 문제를 구체적으로 지적
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Overall Framework

Intelligent Design for Engineering Applications Lab

Part 1

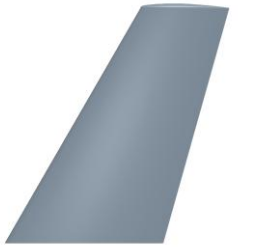
EXP 1

Part 2
Experiment 1

Mesh quality-based remeshing agent framework

Wing input

자연어 요청



SALOME

Initial meshing agent

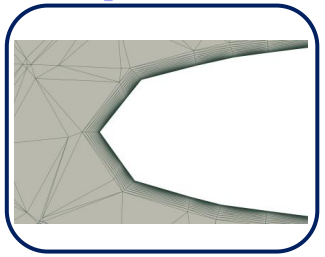
Qwen3.5-9B
(local,Ollama)

"ONERA M6 외부유동 해석 prism-tetra 혼합 격자 생성. 경계층 총 두께 1mm, Mach 0.8395 조건에 y+≈1로 층수 결정."

Qwen

Remeshing agent

Qwen

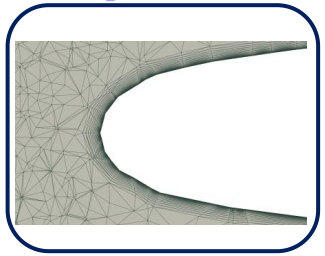


Mesh generation



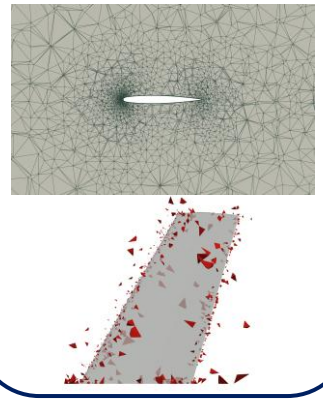
Mesh quality

Qwen



Remeshing

Final mesh



한계 : Mesh quality는 좋아지지만, 유동 해석의 정확도는 보장되지 않아 CFD coupling이 필수

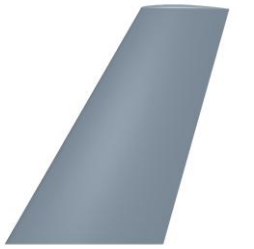
Part 3
Experiment 2

EXP 2

AMR-based remeshing agent framework

Wing input

Initial mesh



ONERA M6

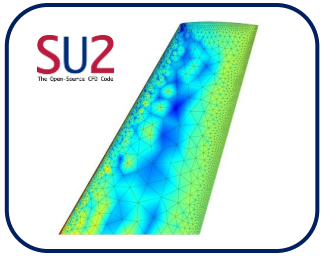
AMR agent

Local agent

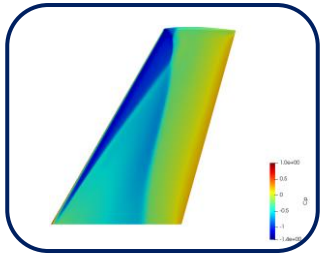
- Cycle condition check
- Parameter control
- Decision

Qwen

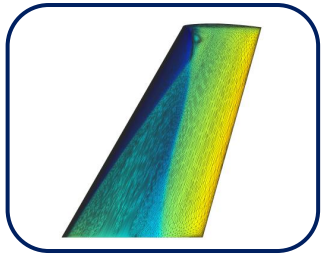
Agent judgment



SU2 CFD solver

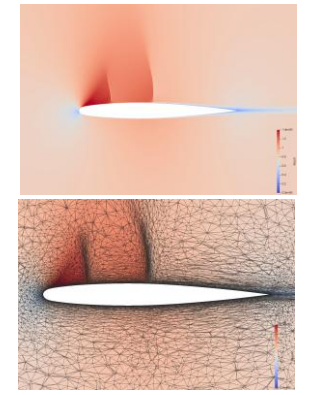


gradient calculate



mesh refinement

Final mesh



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Local Large Language Models(LLM) : Qwen3.5-9B





- Navier-Stokes난제를 AI가 해결함으로써 제기된 미공개 연구 유출 의혹[1]
  - ✓ 미공개 연구자료를 외부 AI 서비스에서 처리할 경우, 데이터 접근 범위에 대한 신뢰 문제가 발생할 수 있음
- Airbus 2025 연차 보고서
  - ✓ On-premise 사용이 명시
  - ✓ 서버 인프라에 AI 플랫폼 구축

[1] Maguire, D., & Bowler, J. (2026). Controversy erupts as OpenAI claims solution to Navier Stokes maths problem. ABC News, September 10, 2026.

Local Large Language Models(LLM) : Qwen3.5-9B

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Additional research question

소형 언어 모델을 이용하여 반복적인 CFD meshing을 대체할 수 있을까?

Qwen3.5-9B **vs.** GPT-3 (175B)

약 19.4배 작은 모델

- N
- 논문의 연구진이 제시한 local LLM의 필요성
  - ✓ 지식재산권 보호 : 비공개 시뮬레이션 코드와 기술 문서를 외부 LLM 제공자에게 전달하지 않을 필요성[2]
  - ✓ 연구데이터 보호 : 내부 프로젝트 데이터와 관련 정보에 대한 통제[2]

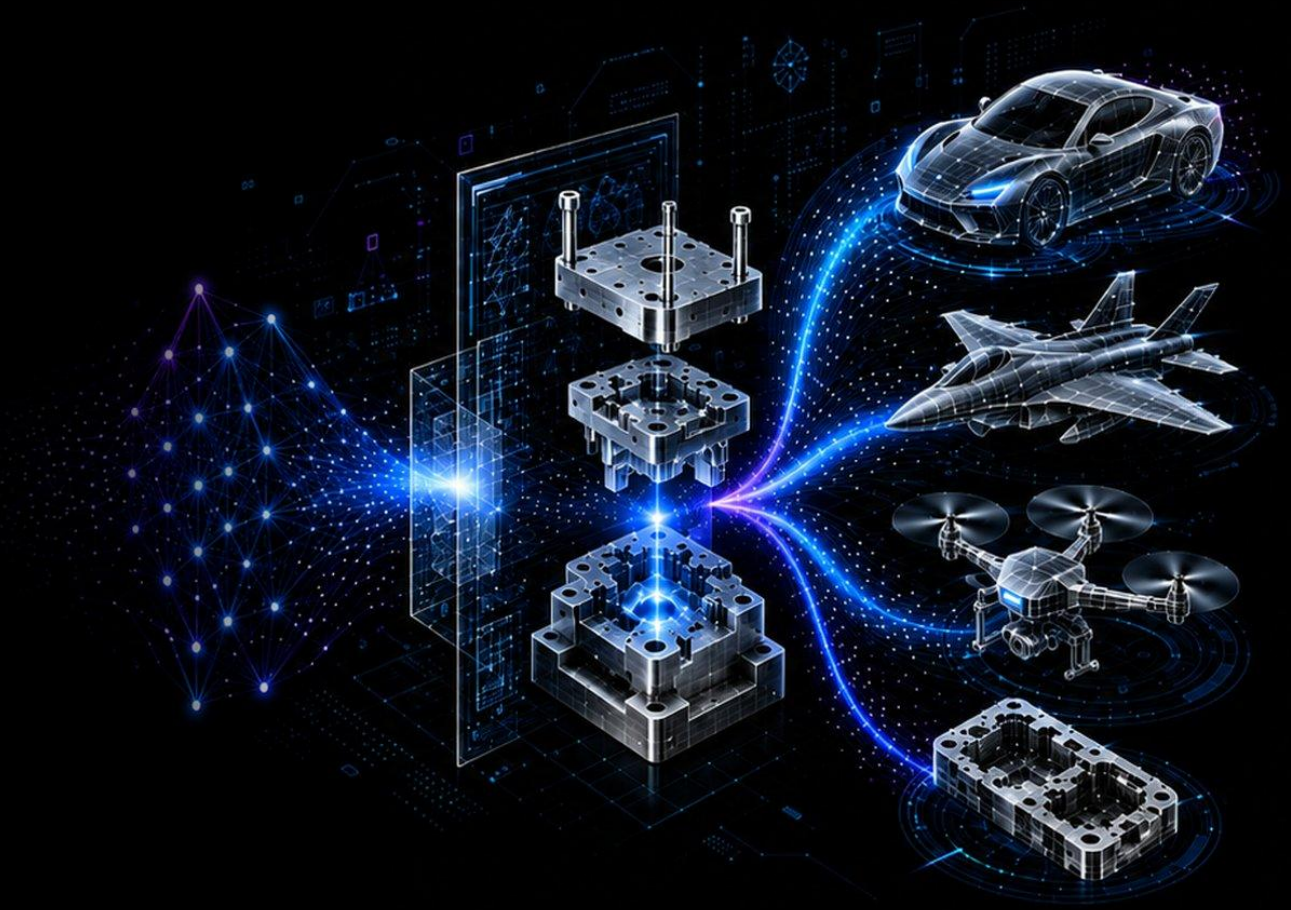
[1] Maguire, D., & Bowler, J. (2026). Controversy erupts as OpenAI claims solution to Navier Stokes maths problem. ABC News, September 10, 2026.

PART

II

Experiment 1

Mesh quality-based remeshing agent



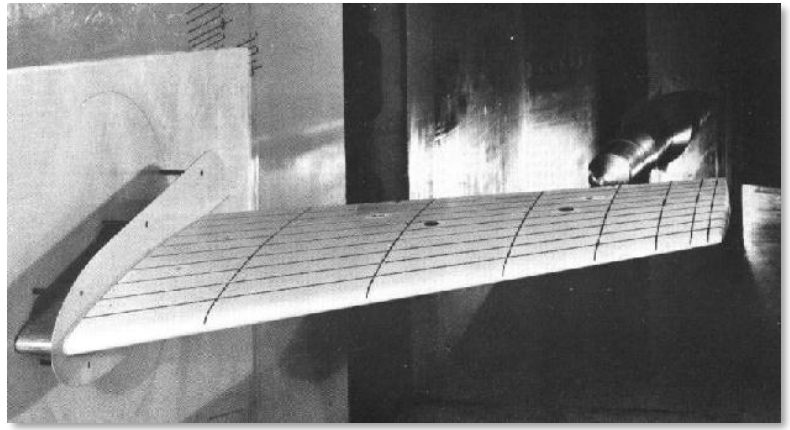
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Wing Geometry

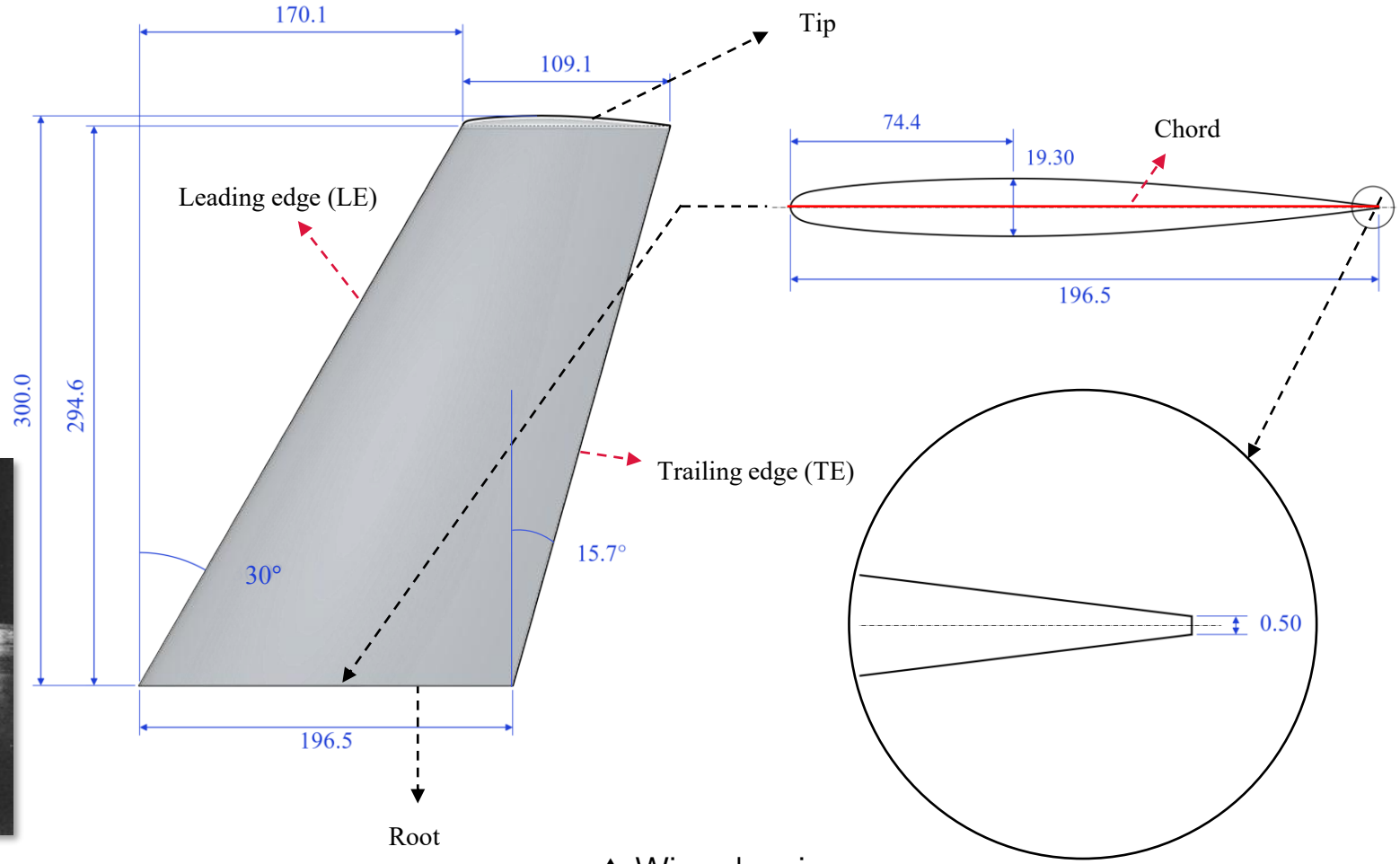
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Input wing geometry

- ONERA M6
- Mach 0.8395
- Chord의 1%만큼 TE쪽 edge 절단
- Scale Factor = 0.2463



▲ ONERA M6 wing



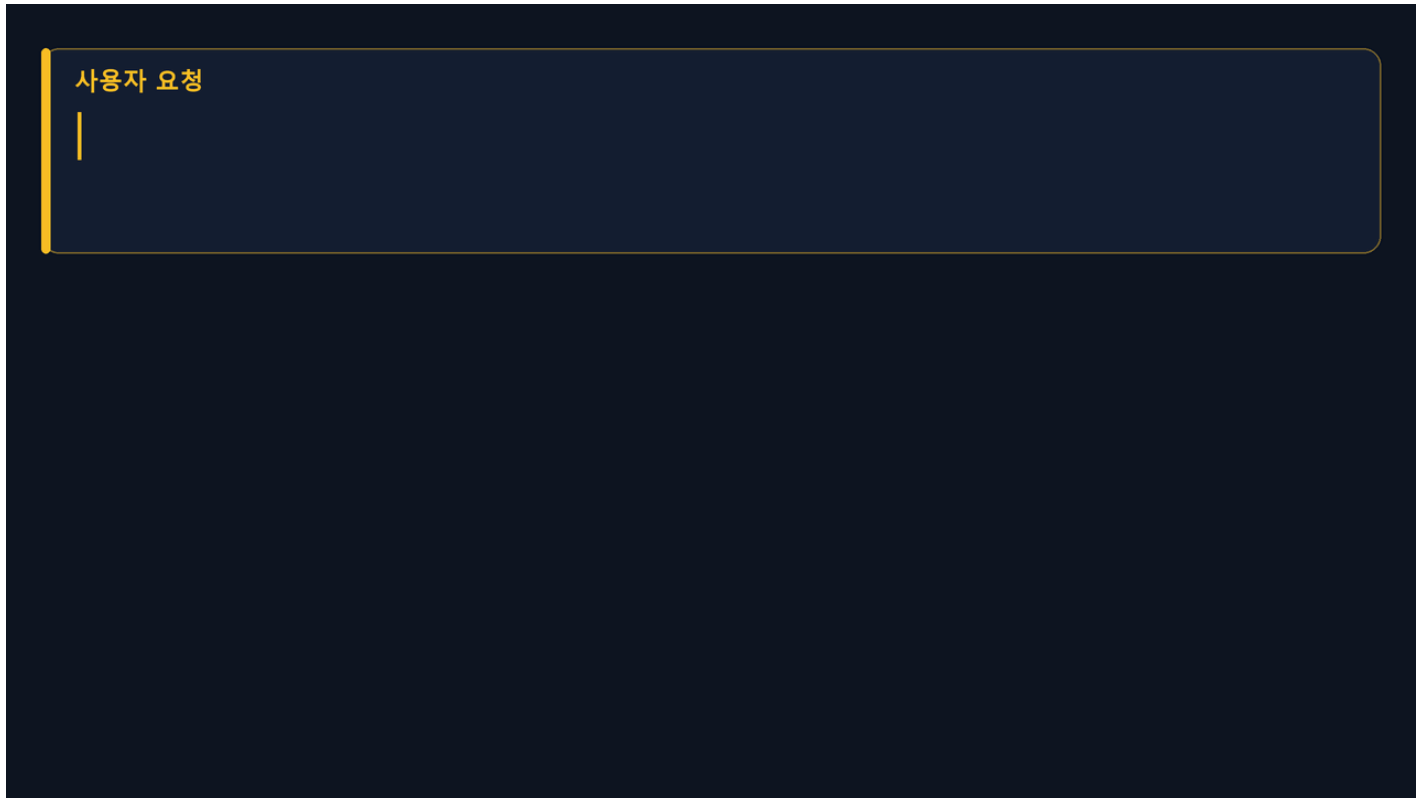
▲ Wing drawing

Initial Meshing Agent

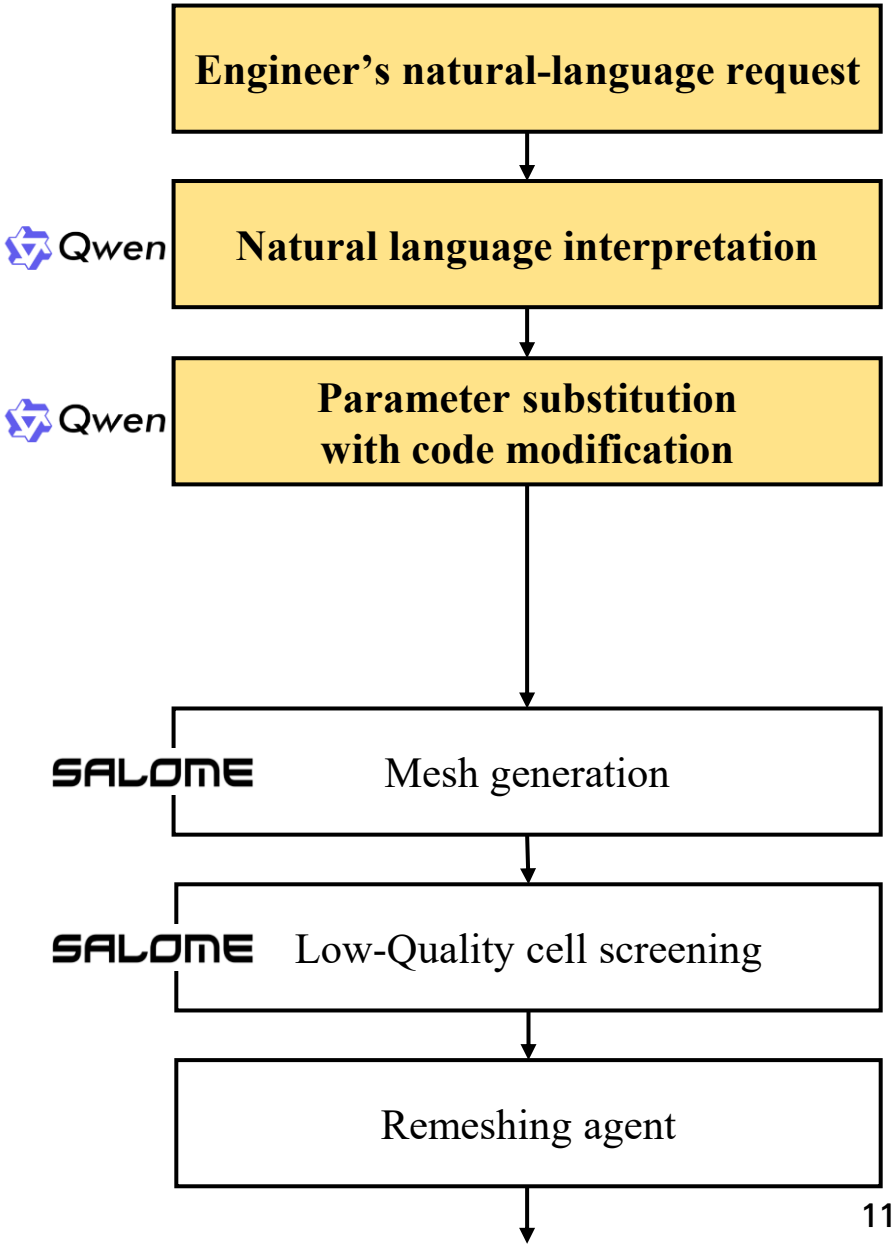
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Initial meshing agent

- 자연어 요청
  - ✓ ONERA M6, 외부유동 해석 prism-tetra 혼합격자 생성. 경계층 총 두께 1mm, 유속 Mach 0.8395, y+=1로 층수 결정. 격자 수 200만개 이내로 품질 개선까지.



▲ Initial mesh generation

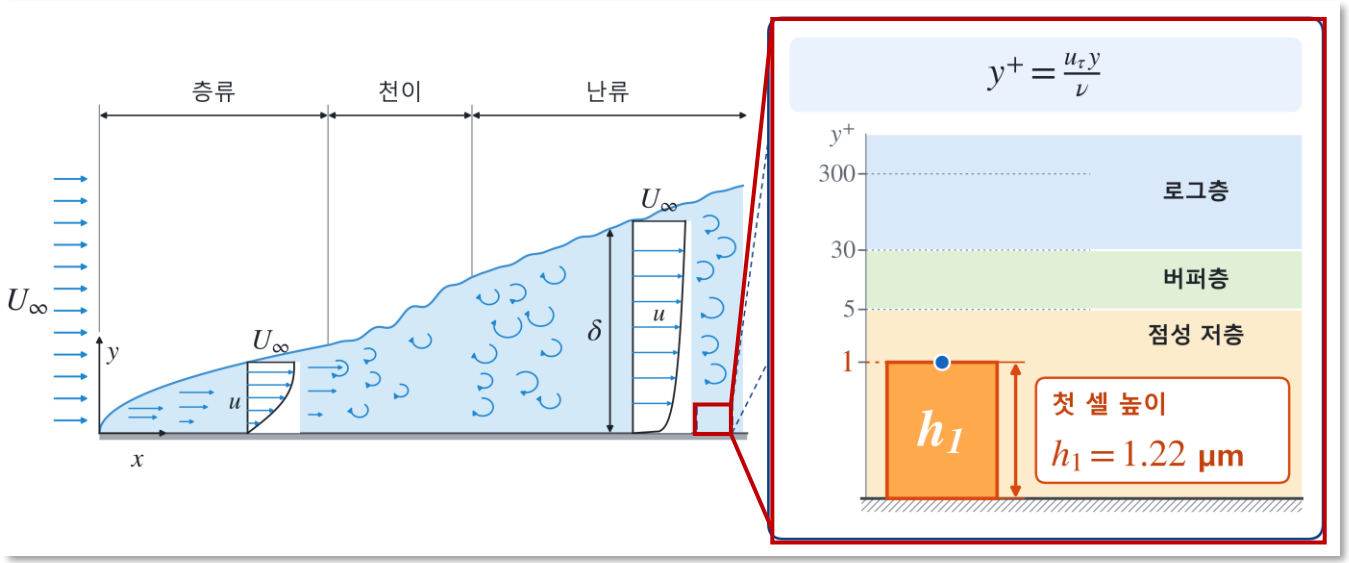


Initial Meshing Agent

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Flow condition and y+

- y^+ 란?
  - ✓ 벽면에서 첫 번째 격자 중심까지의 무차원 거리
  - ✓ $y^+ \approx 1$ 은 첫 셀을 viscous sublayer안에 두기 위한 조건
- Agent 내부의 wall y+ calculator 존재
- Mach 0.8395



▲ y+ 경계층 첫 셀 높이

Engineer's natural-language request

Qwen Natural language interpretation

Qwen Parameter substitution with code modification

SALOME Mesh generation

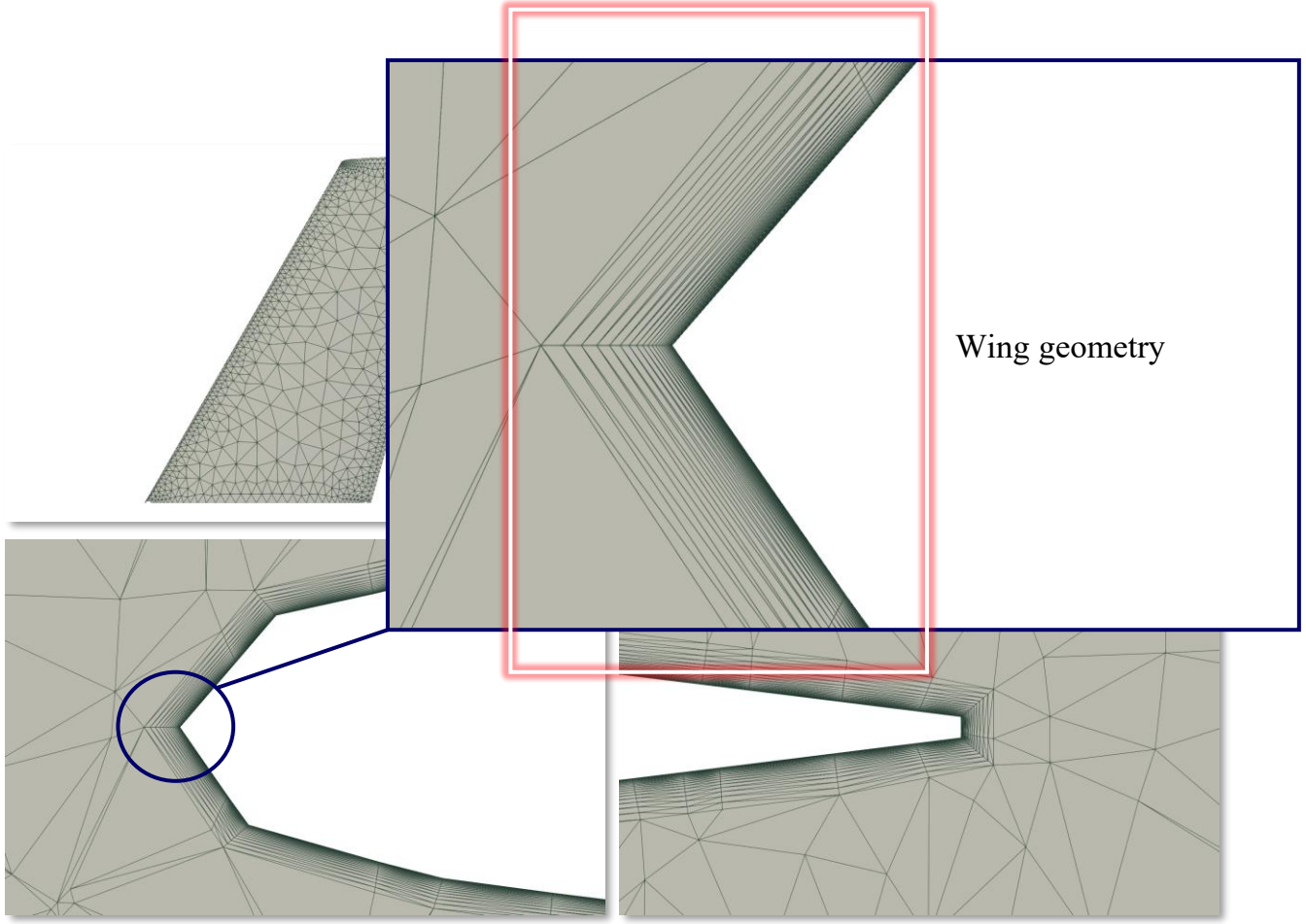
SALOME Low-Quality cell screening

Remeshing agent

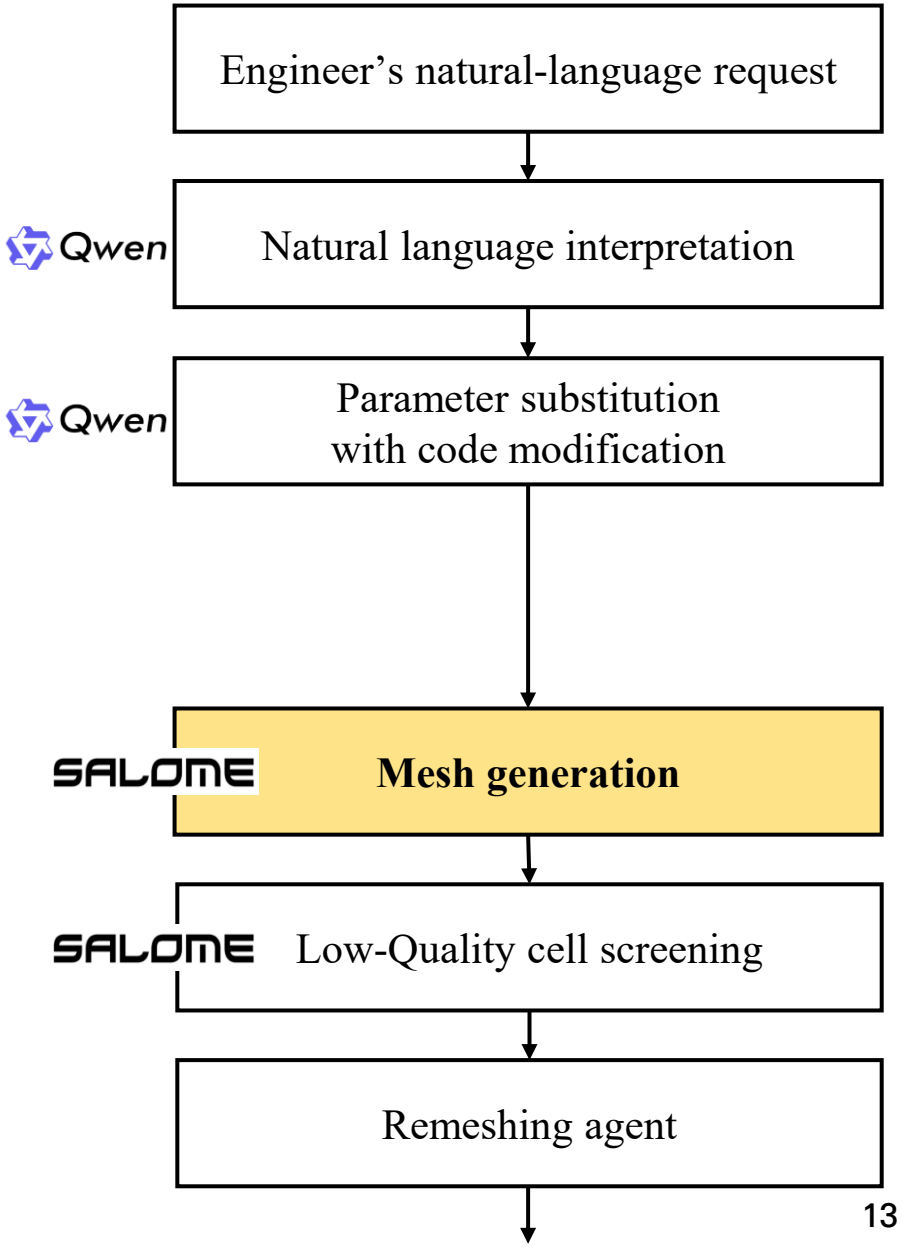
Initial Meshing Agent

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Initial meshing agent



▲ Initial mesh view



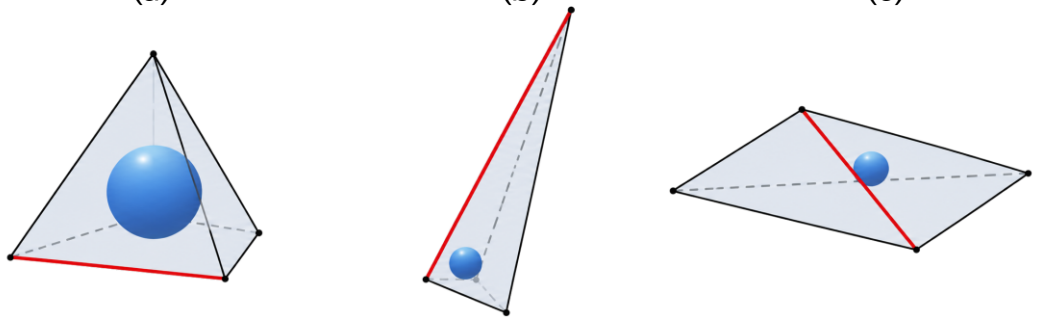
Screening criteria

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Defective grid screening

- Aspect Ratio
  - ✓ 가장 긴 변 ÷ $(2\sqrt{6}\times r)$ (r : 내접하는 구의 반지름)
- Scaled Jacobian (정규화된 Jacobian 값)
  - ✓ $SJ = min\sqrt{2}\frac{e_3\cdot(e_1\times e_2)}{|e_1||e_2||e_3|}$
- Chordal deviation (LE chordal deviation)
  - ✓ CAD 곡면과 격자 표면 사이의 기하학적 거리 편차

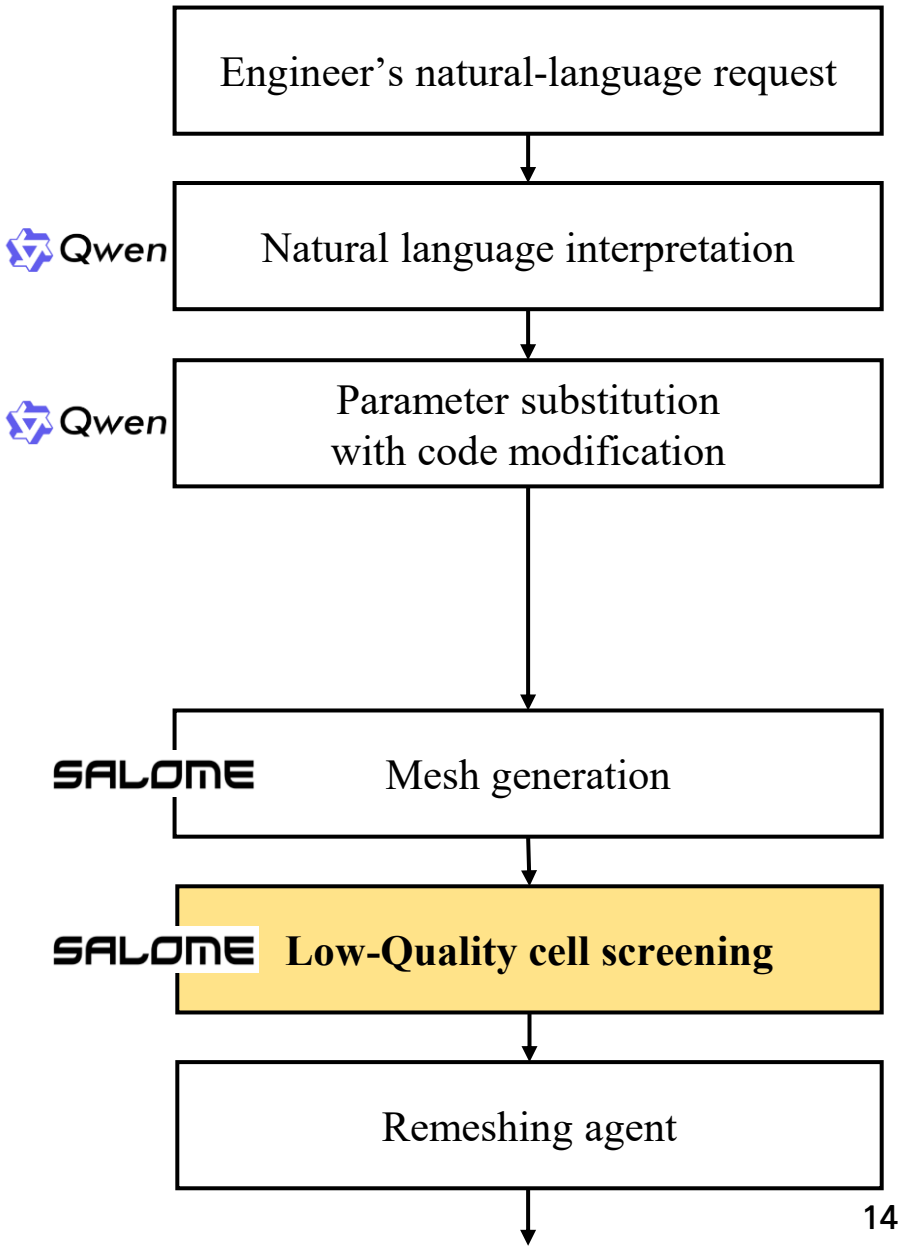
(a) (b) (c)



(a) Aspects ratio = 1.00

(b) Aspects ratio = 4.82

(c) Aspects ratio = 5.83

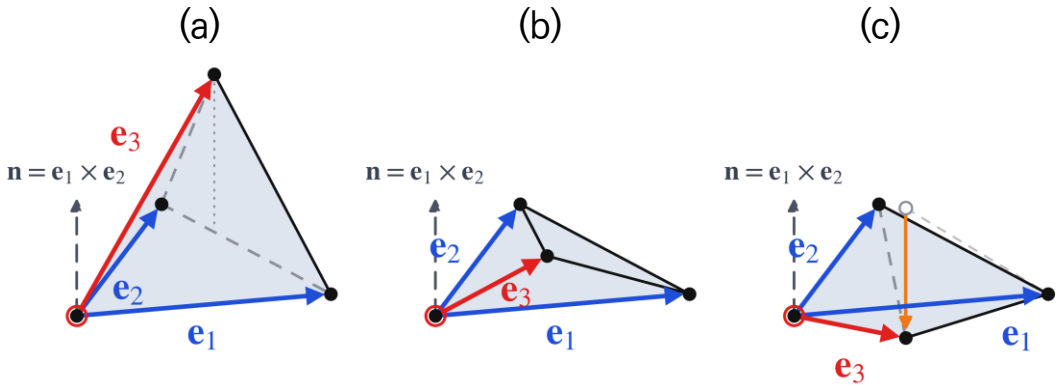


Screening criteria

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Defective grid screening

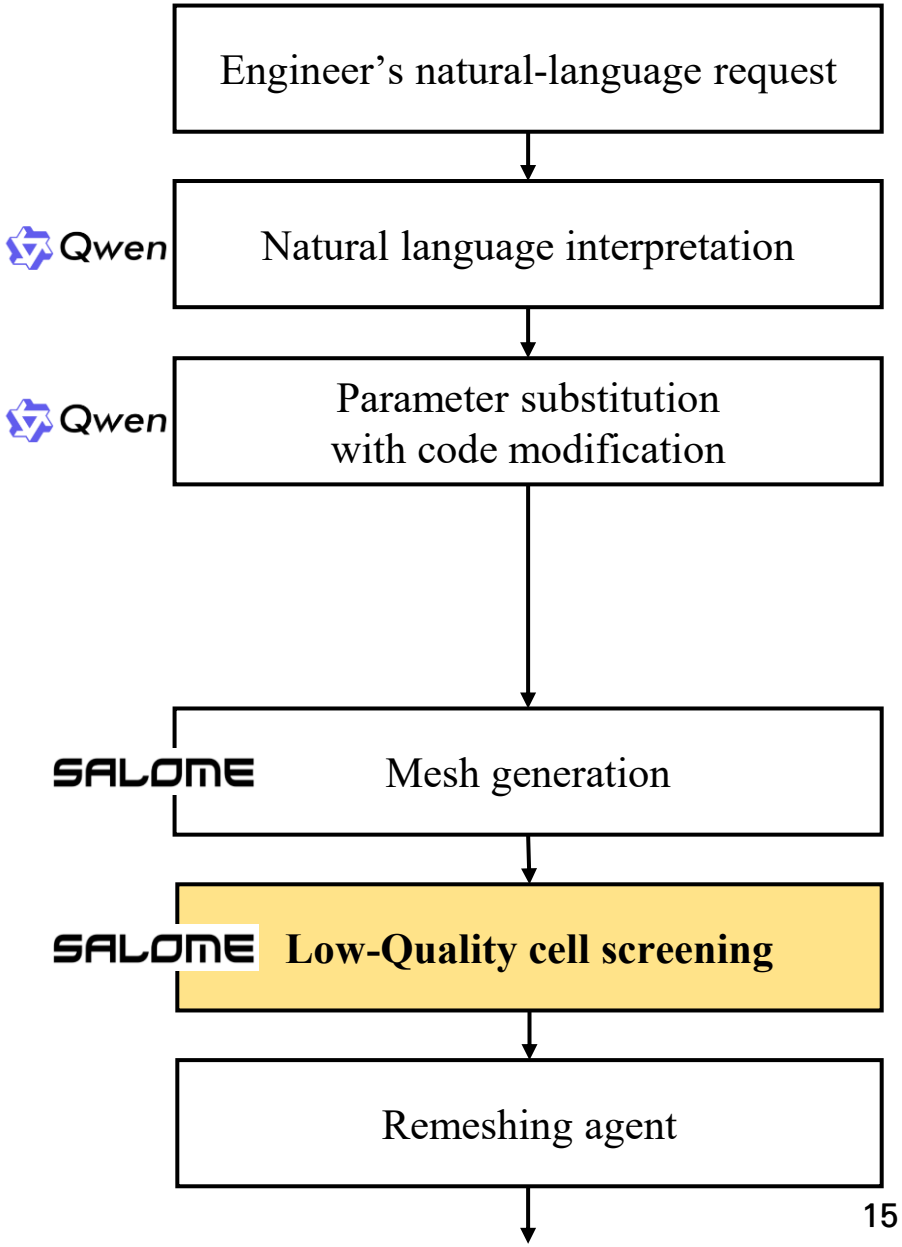
- Aspect Ratio
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(a) Scaled Jacobian = 1.00

(b) Scaled Jacobian = 0.15

(c) Scaled Jacobian 〈 0



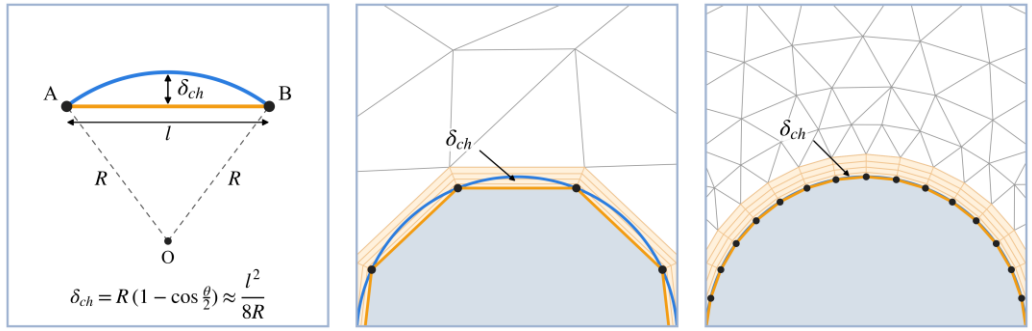
Screening criteria

Part 1 Introduction
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Defective grid screening

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- Chordal deviation (LE chordal deviation)
  - ✓ CAD 곡면과 격자 표면 사이의 기하학적 거리 편차

(a) (b) (c)



(a) Mathematical chordal deviation principle

(b) High chordal deviation

(c) Low chordal deviation

Engineer's natural-language request

↓

Qwen Natural language interpretation

↓

Qwen Parameter substitution with code modification

↓

SALOME Mesh generation

↓

SALOME **Low-Quality cell screening**

↓

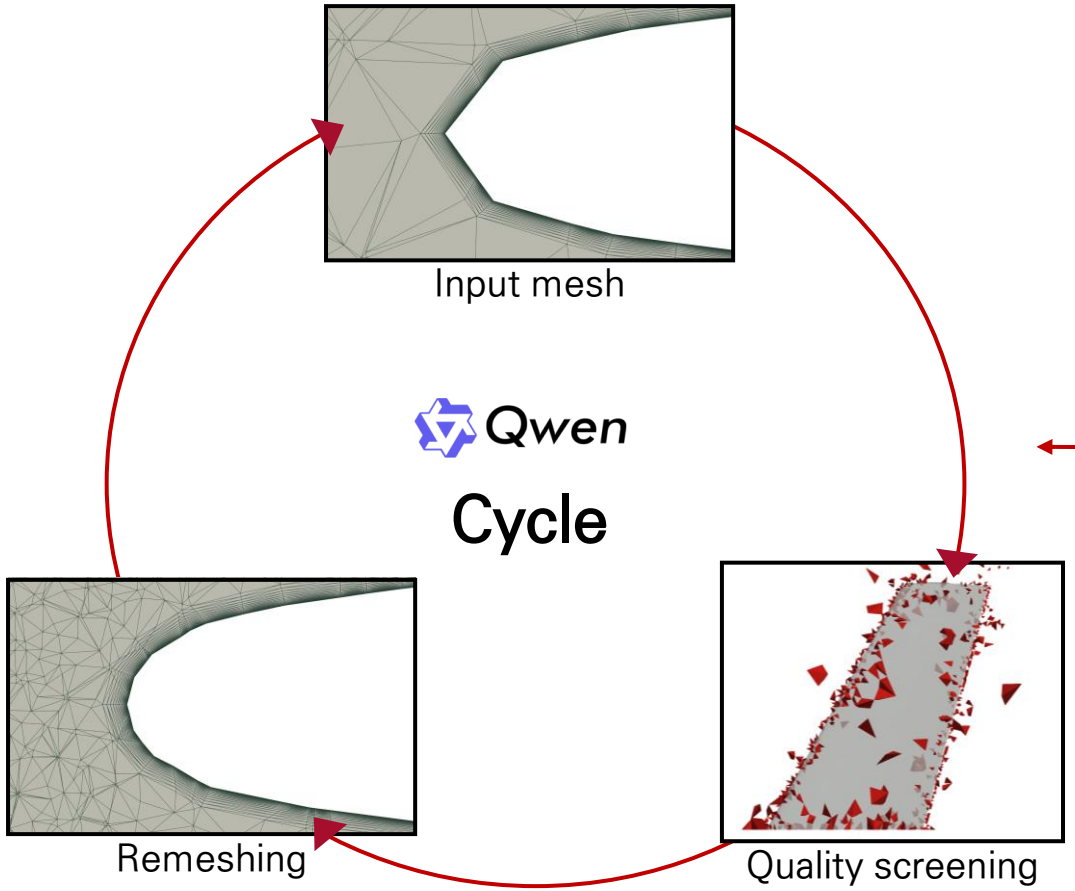
Remeshing agent

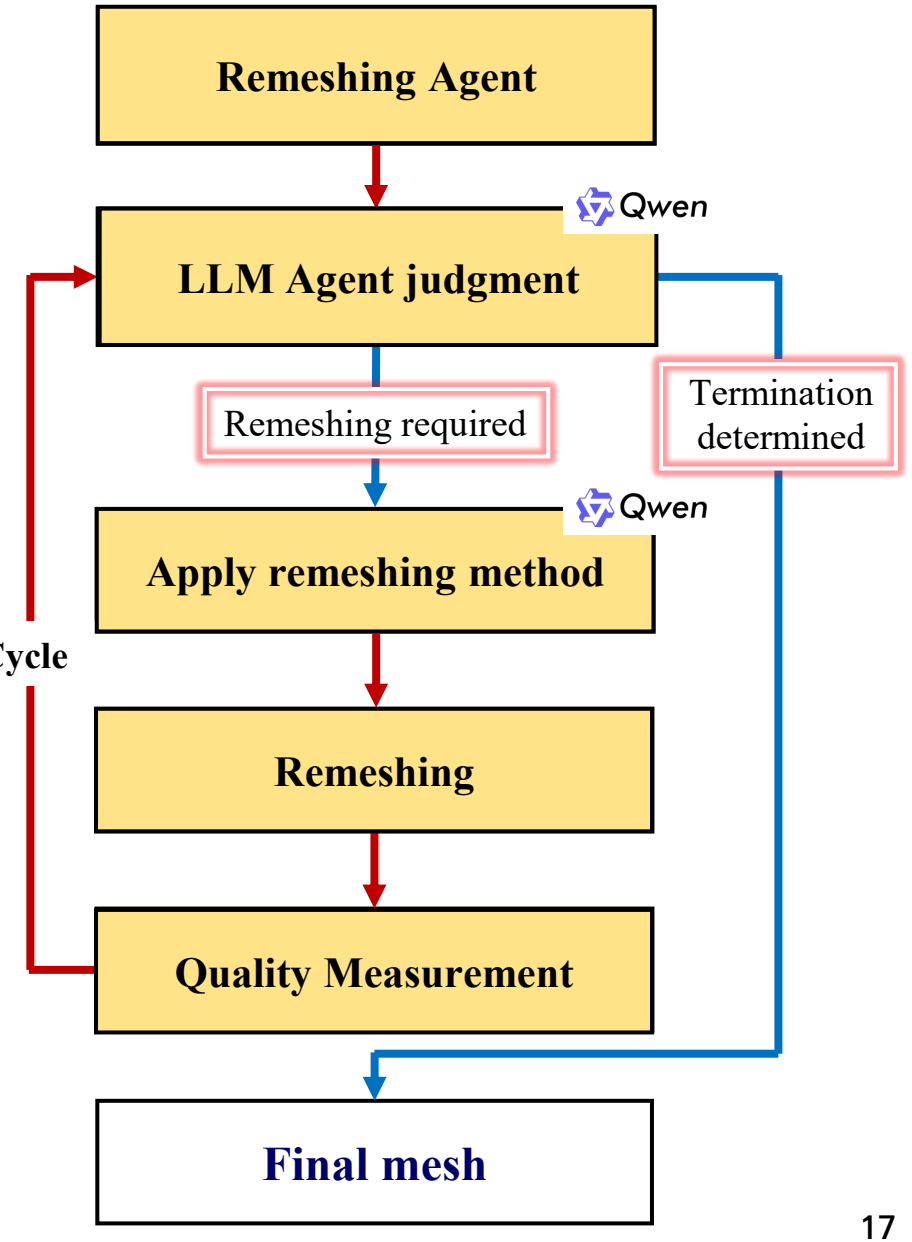
Remeshing agent

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Remeshing agent pipeline

- 초기 격자 생성 후 remeshing agent로 전달



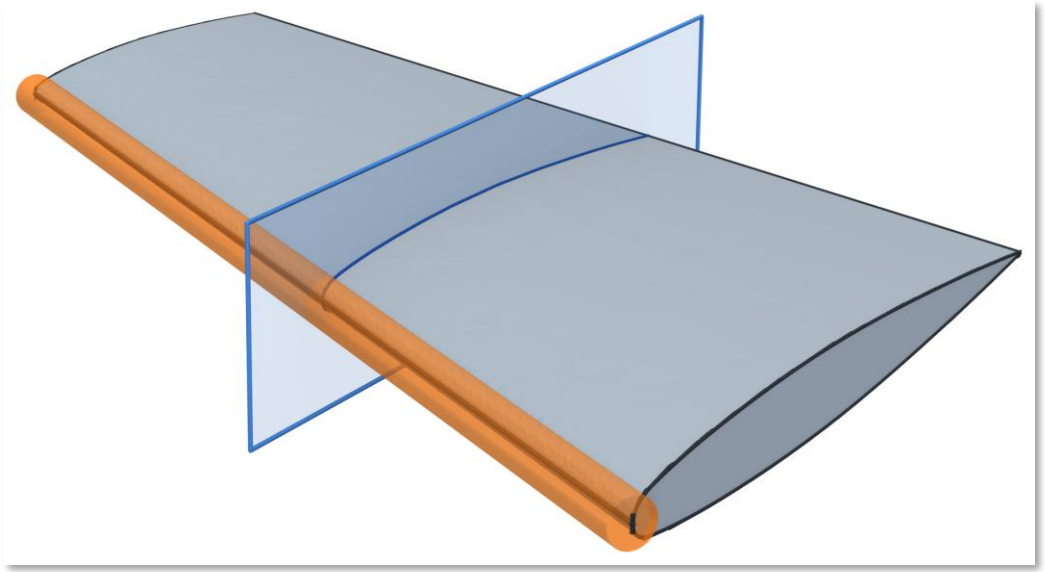


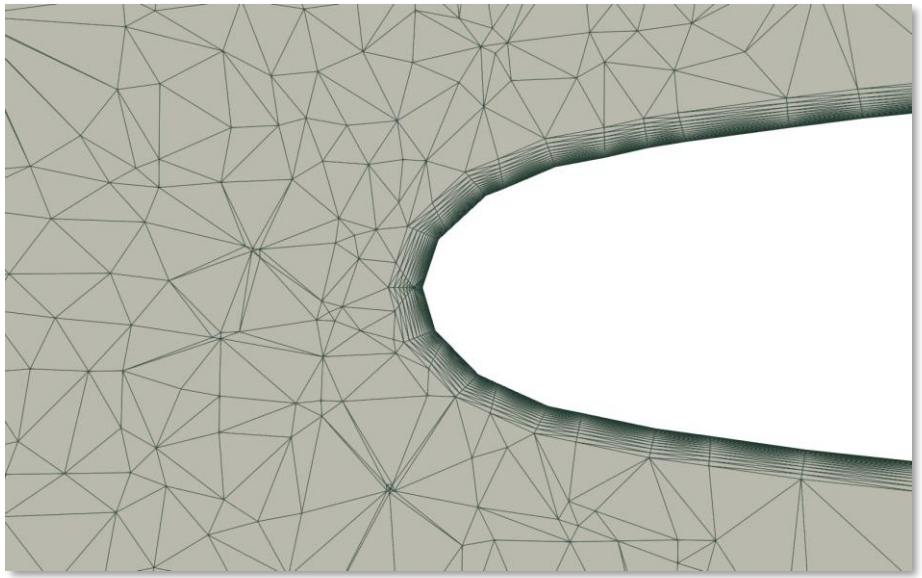
Remeshing method

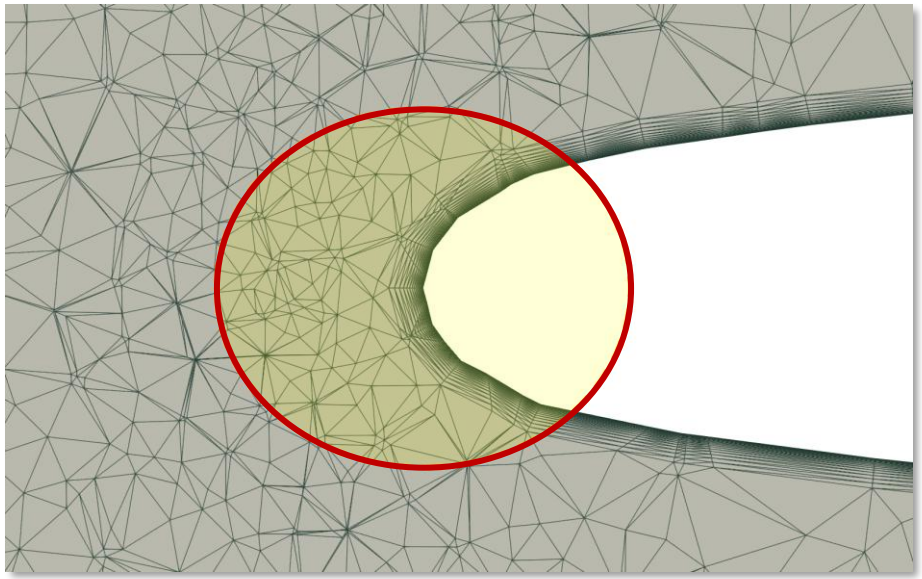
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Geometry remeshing

- LE를 따라 원기둥을 생성하고, 원기둥 내부 tetra 사이즈를 조절
  - ✓ 경계층 표면의 삼각형과 tetra 내부의 사면체의 변의 길이를 맞추는 역할
- Cylinder geometry
  - ✓ LE edge를 축으로 반지름 6 mm
  - ✓ 내부 tetra 크기 = LE 1D mesh 크기의 1.0 ~ 1.25 배





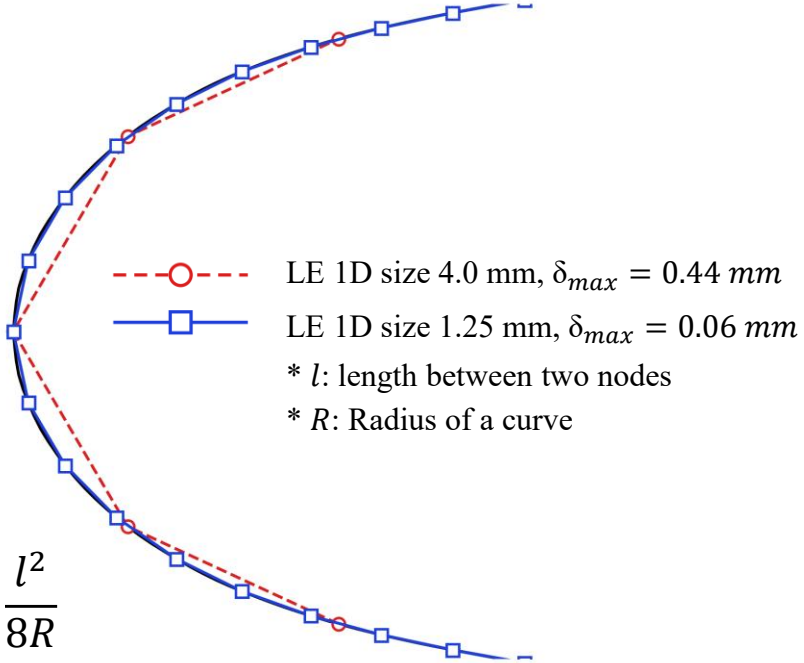


Remeshing method

Part 1 Introduction
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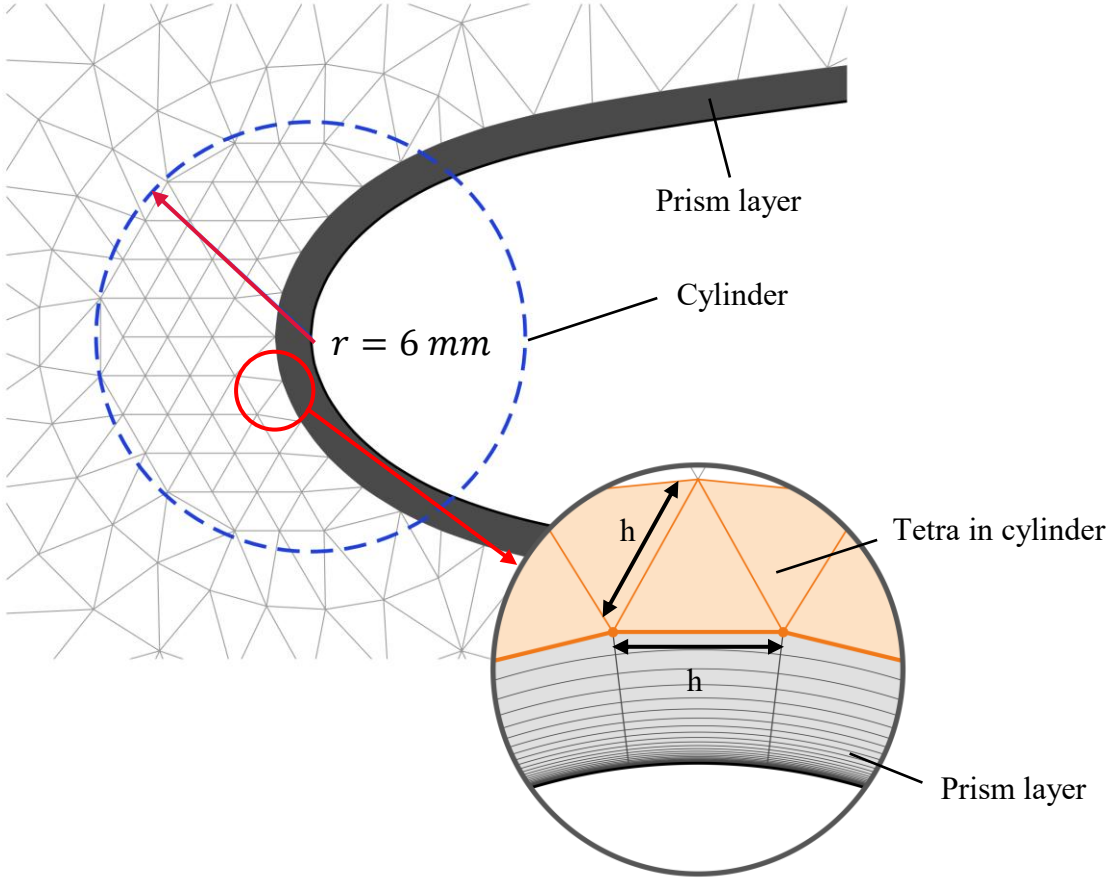
Agent local size remeshing

(a) LE 1D edge size for chordal deviation



$$\delta \approx \frac{l^2}{8R}$$

(b) LE cylinder (r = 6 mm) along the LE line



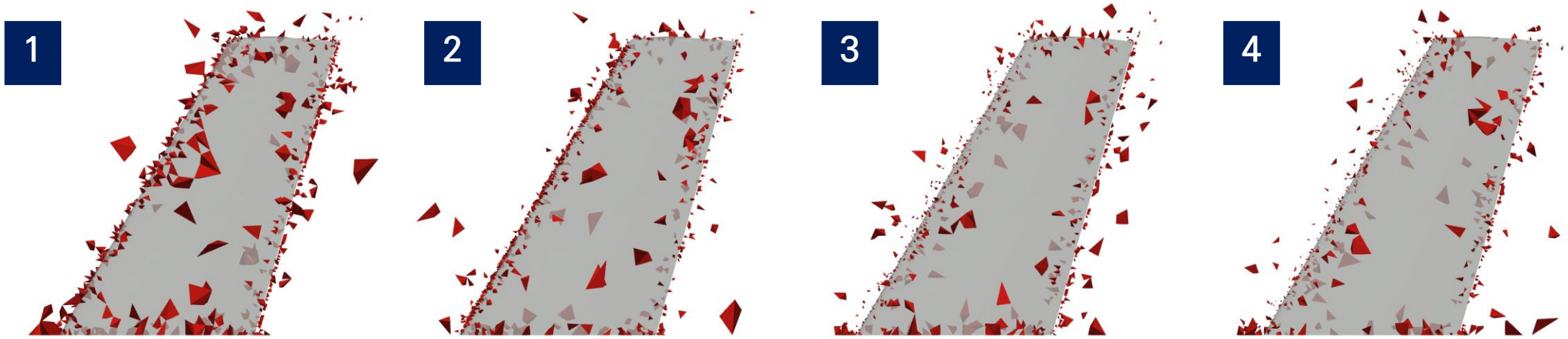
(a) L.E./T.E. 1차원 edge의 크기를 줄이며 chordal deviation 감소

(b) L.E.를 따라 원기둥 띠 (r = 6 mm)를 배치해 원기둥 내부의 tetra 크기를 경계층 최상층과 맞춤

Results : Quality Screening per Cycle

Part 1 Introduction
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Defective grid screening



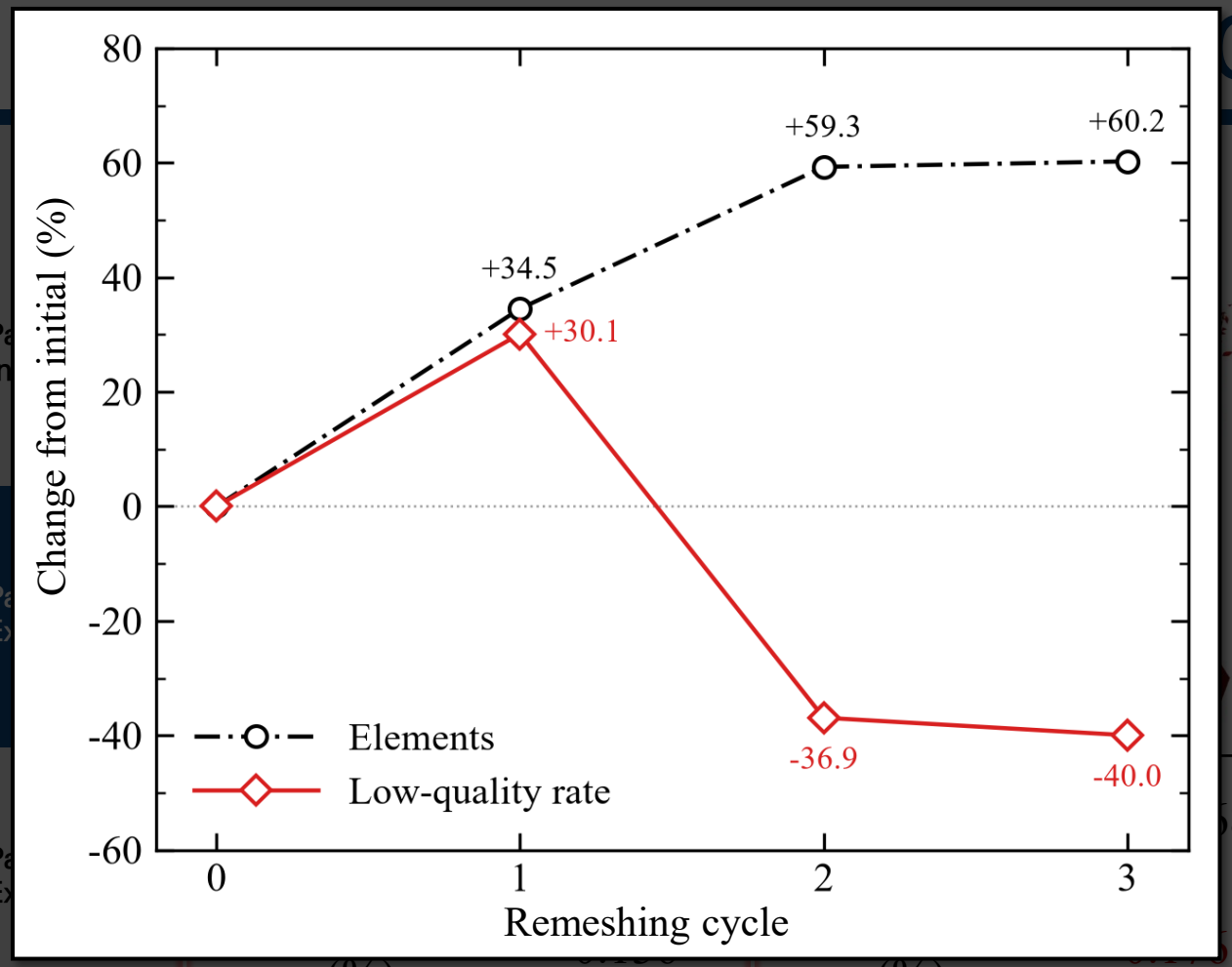
1		2		3		4	
Element	599,451	Element	806,368	Element	954,792	Element	**960,524 (+361,073)**
Low-quality (%)	0.136	Low-quality (%)	0.176	Low-quality (%)	0.086	Low-quality (%)	**0.081 (-40%)**

▲ Final vs Initial

Element (+206,917)
Low-quality (+30.1%)

Element (+148,424)
Low-quality (−51.5%)

Element (+5,732)
Low-quality (−4.9%)







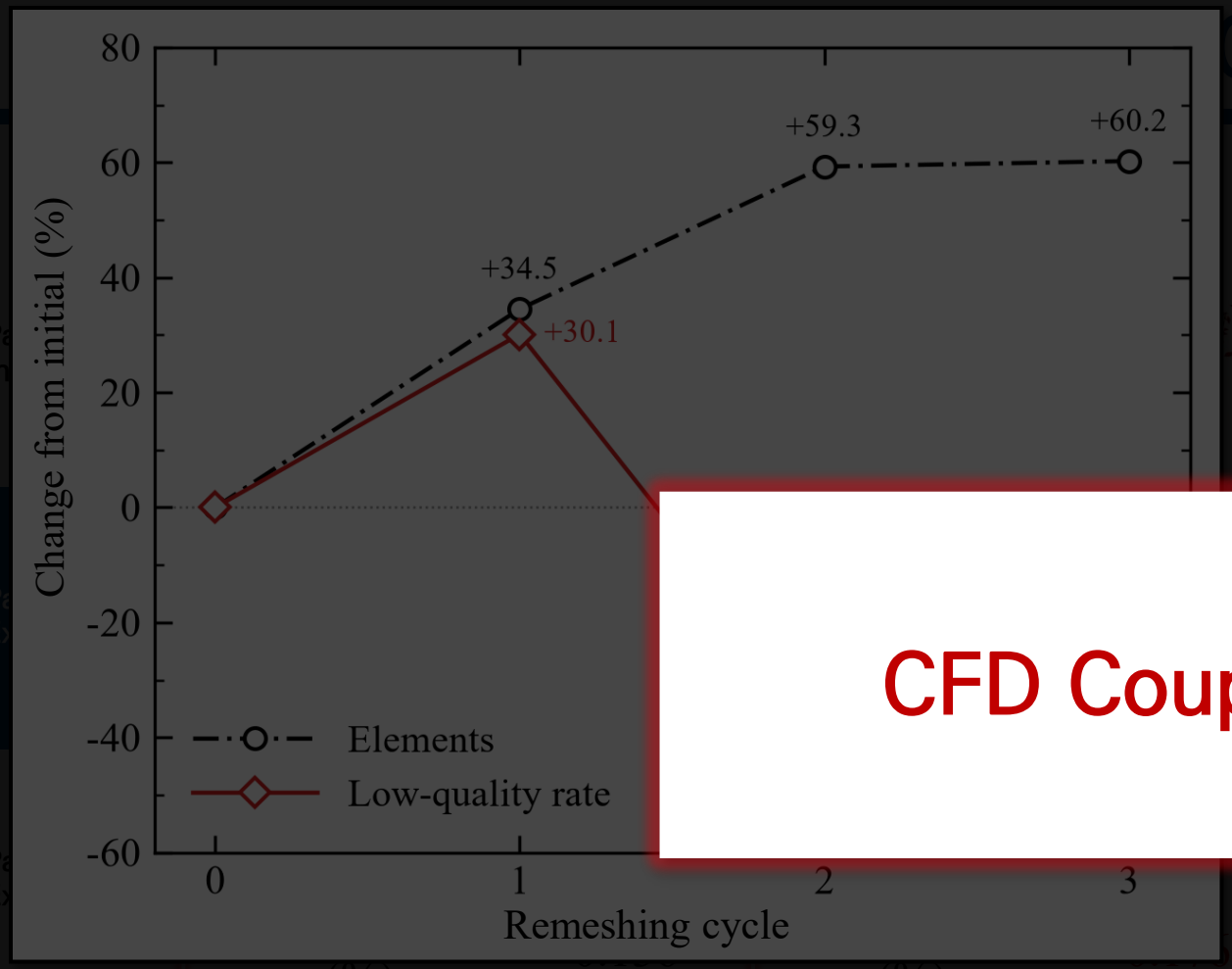
(%)		Element	954,792
(%)		Low-quality (%)	0.086

Element	**960,524 (+361,073)**
Low-quality (%)	**0.081 (-40%)**

▲ Final vs Initial

1 → 2	2 → 3	3 → 4
L.E. 1D **4.0mm** → L.E. 1D **1.4mm**	No Cylinder → Cylinder **1.4mm**	Cylinder **1.4mm** → Cylinder **1.25mm**

Part 4 Conclusion



CFD Coupling 필요



Element	960,524 (+361,073)	
Low-quality (%)	0.081 (-40%)	0.086

▲ Final vs Initial

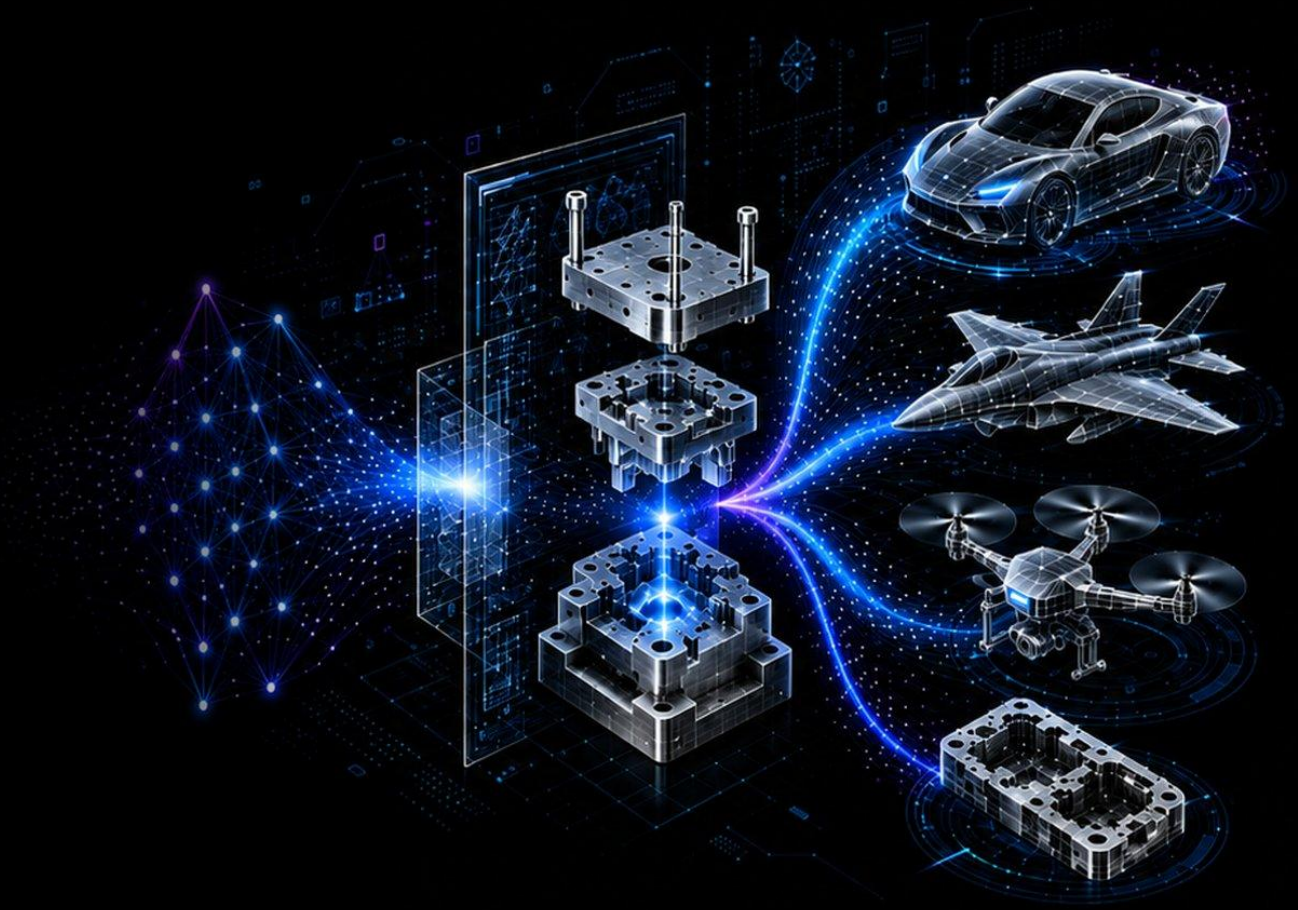
1 → 2	2 → 3	3 → 4
L.E. 1D 4.0mm → L.E. 1D 1.4mm	No Cylinder → Cylinder 1.4mm	Cylinder 1.4mm → Cylinder 1.25mm

PART

III

Experiment 2

AMR-based Remeshing Agent



I II III IV

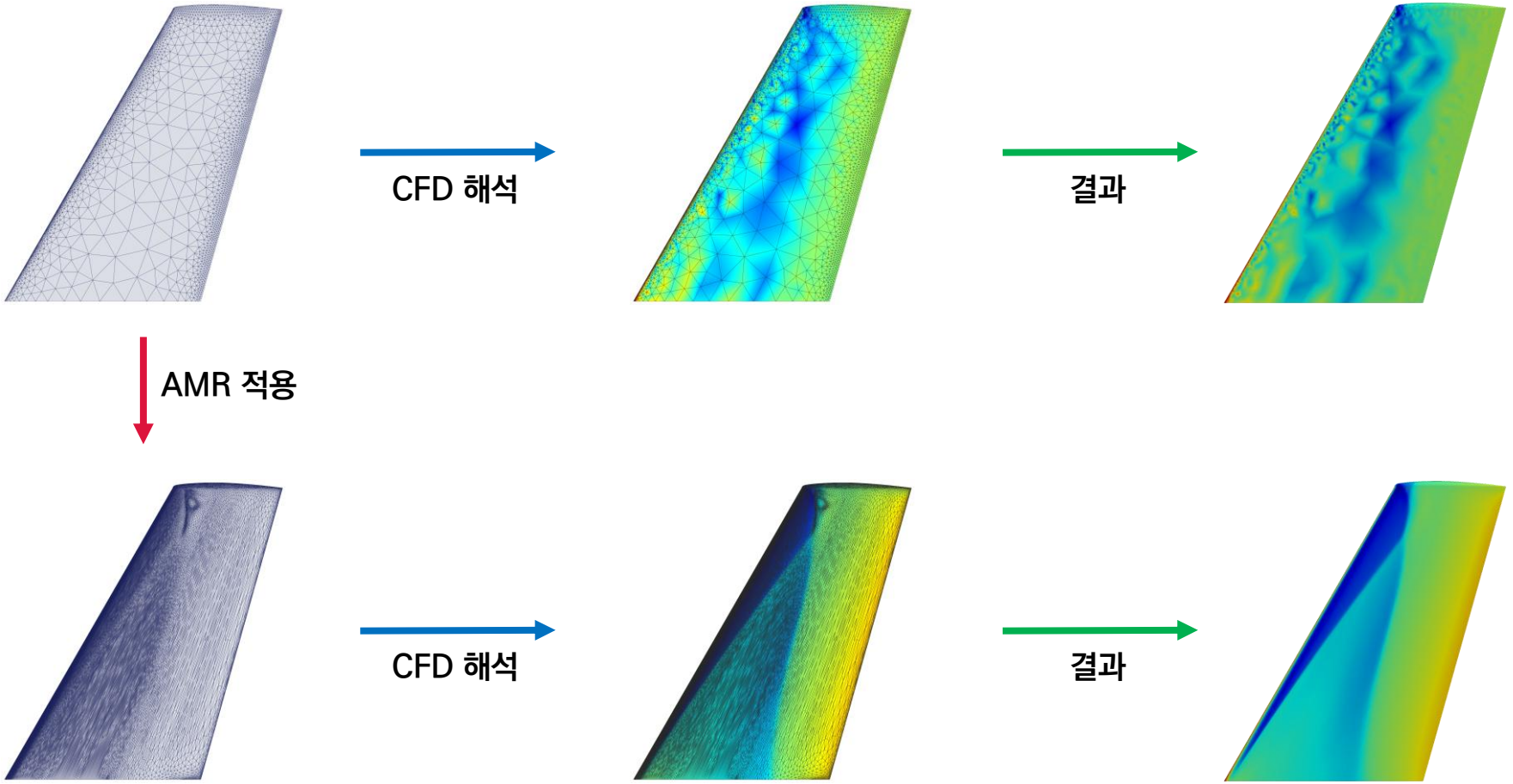
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What is AMR?

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Adaptive Mesh Refine (AMR)

- 해석 결과에 기반, 필요한 영역의 격자만 선택적 refine
- 격자의 효율 향상

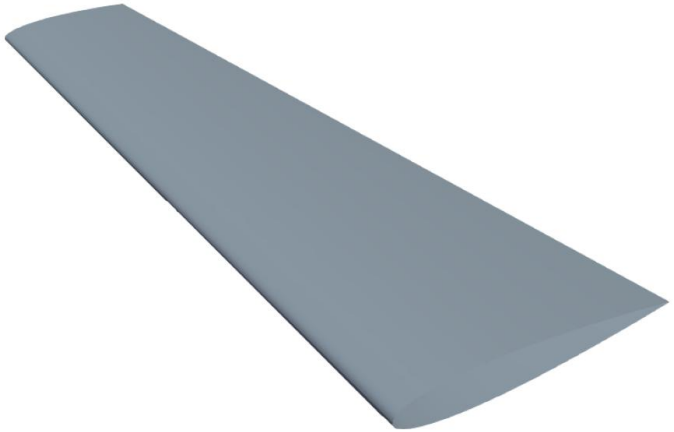


Wing Geometry

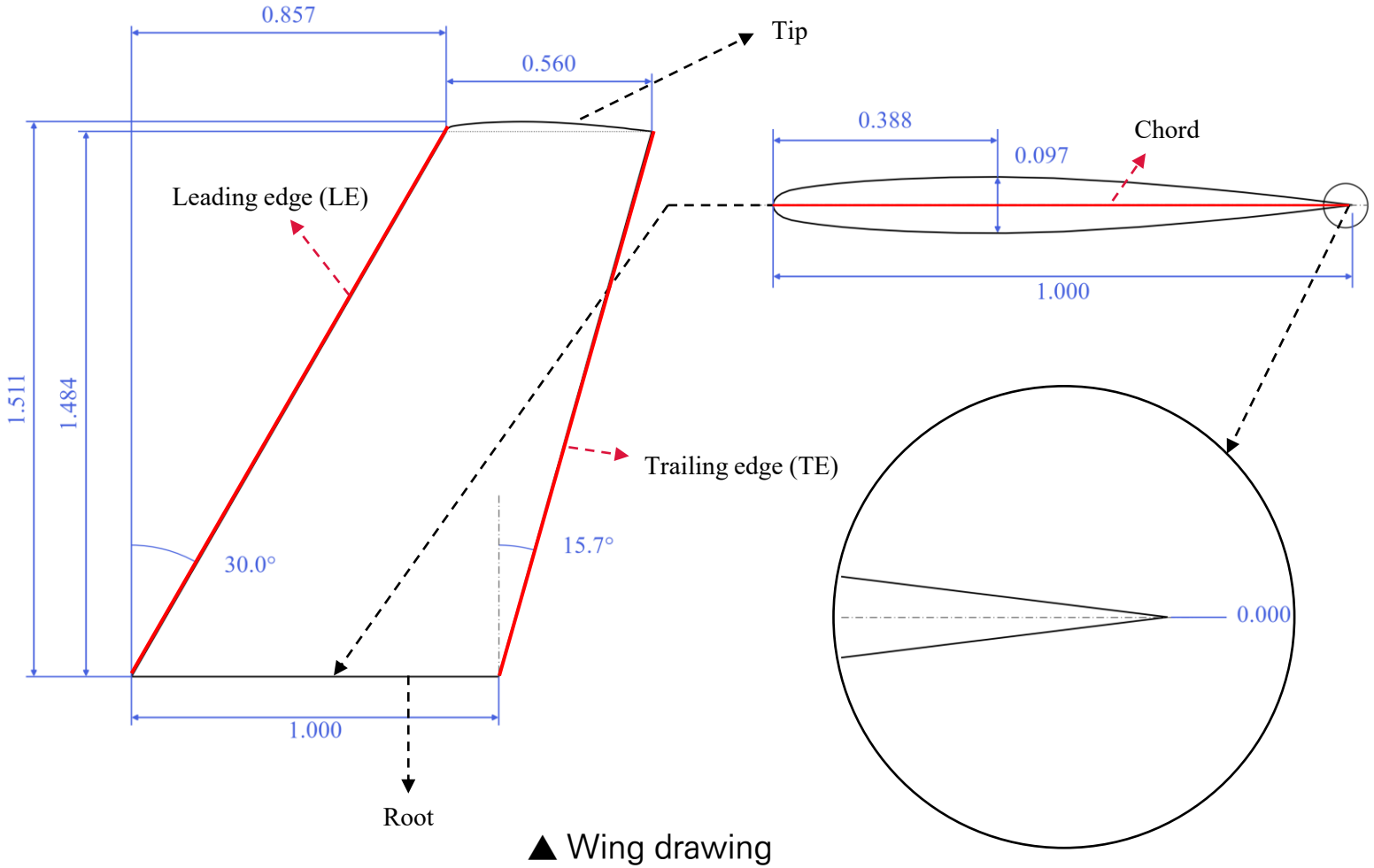
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Input wing geometry

- ONERA M6
- Mach 0.8395



▲ Isometric view



▲ Wing drawing

Flow condition

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유동 조건

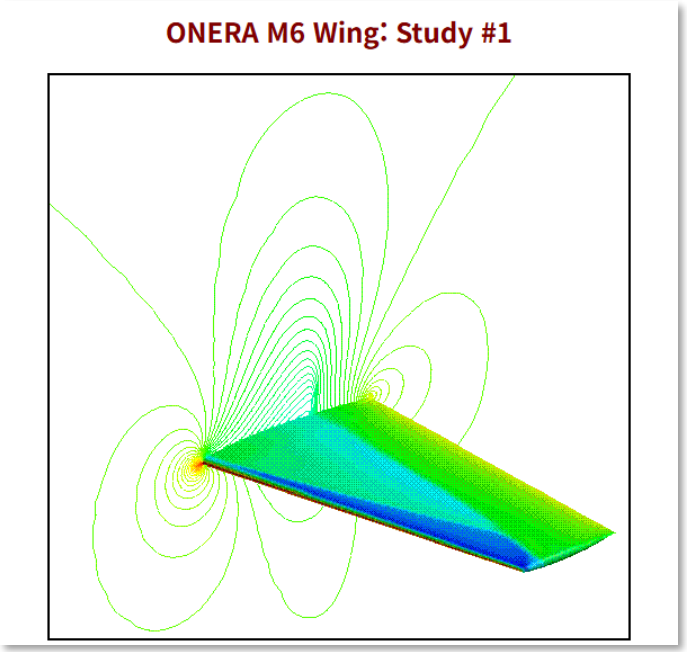
- Mach : 0.8395
- 받음각 : 3.06°
- Re 수 : 11.72×10^{6}

Table 1. Flow conditions for Test 2308 of Ref. 1.

Mach	Reynolds Number	Angle-of-Attack (deg)	Angle-of-Sideslip (deg)
0.8395	11.72E+06	3.06	0.0

지배 방정식

- 압축성 기체
- RANS solver
- Spalart-Allmaras 난류 모델
- 이상기체 공기

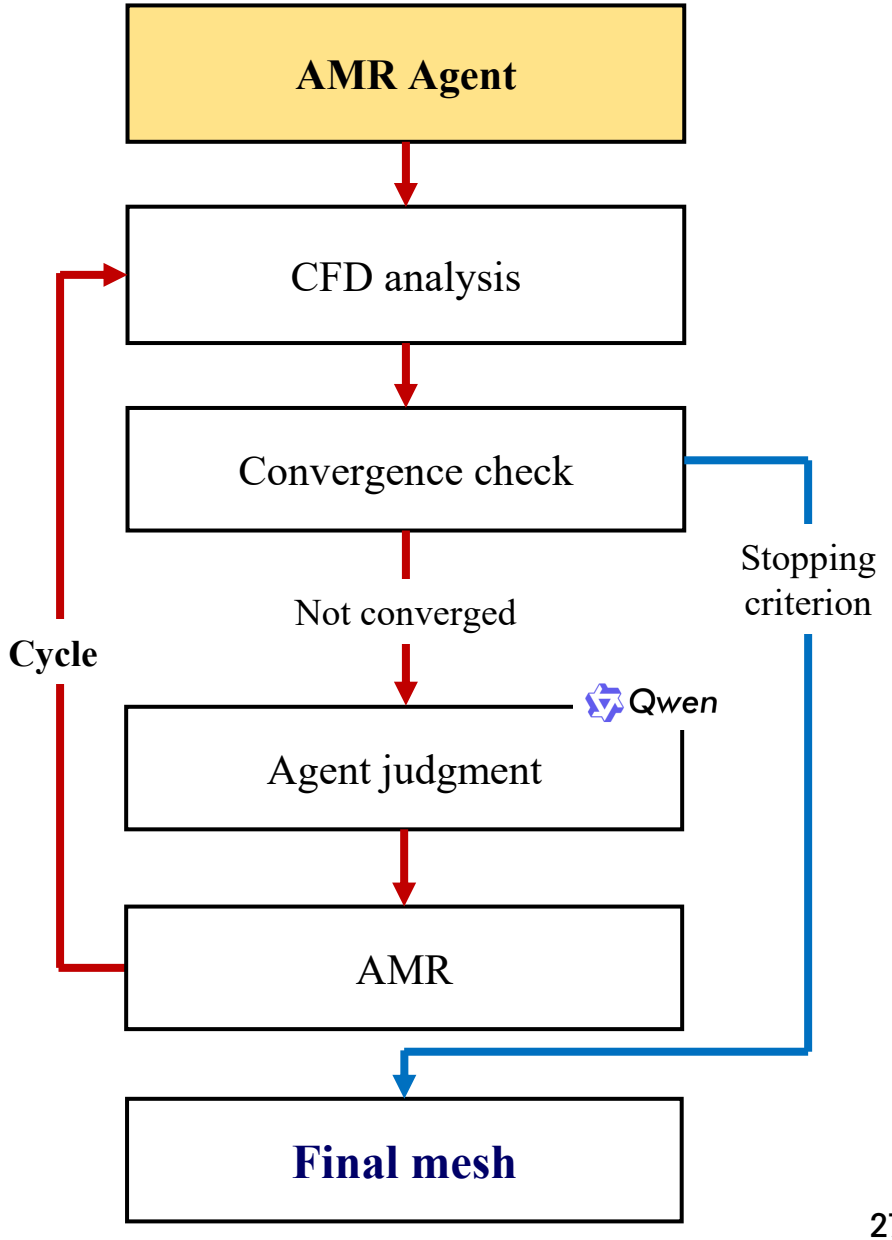


▲ NASA ONERA M6 CFD validation

Agent-Control Parameters

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Parameters	Operation
Complexity	생성할 격자의 전체 규모 설정
Gradation	격자 크기가 급변하지 않도록 조절
Aspect ratio limit	격자의 aspect ratio 제한
Adaptation passes	격자 조정의 반복 횟수
Multi-Grid Levels	계산 수렴 가속
4^{th} order artificial dissipation coefficient(JST)	계산 중 발생하는 수치적 진동억제
CFL number	계산 시간 간격의 크기 조절

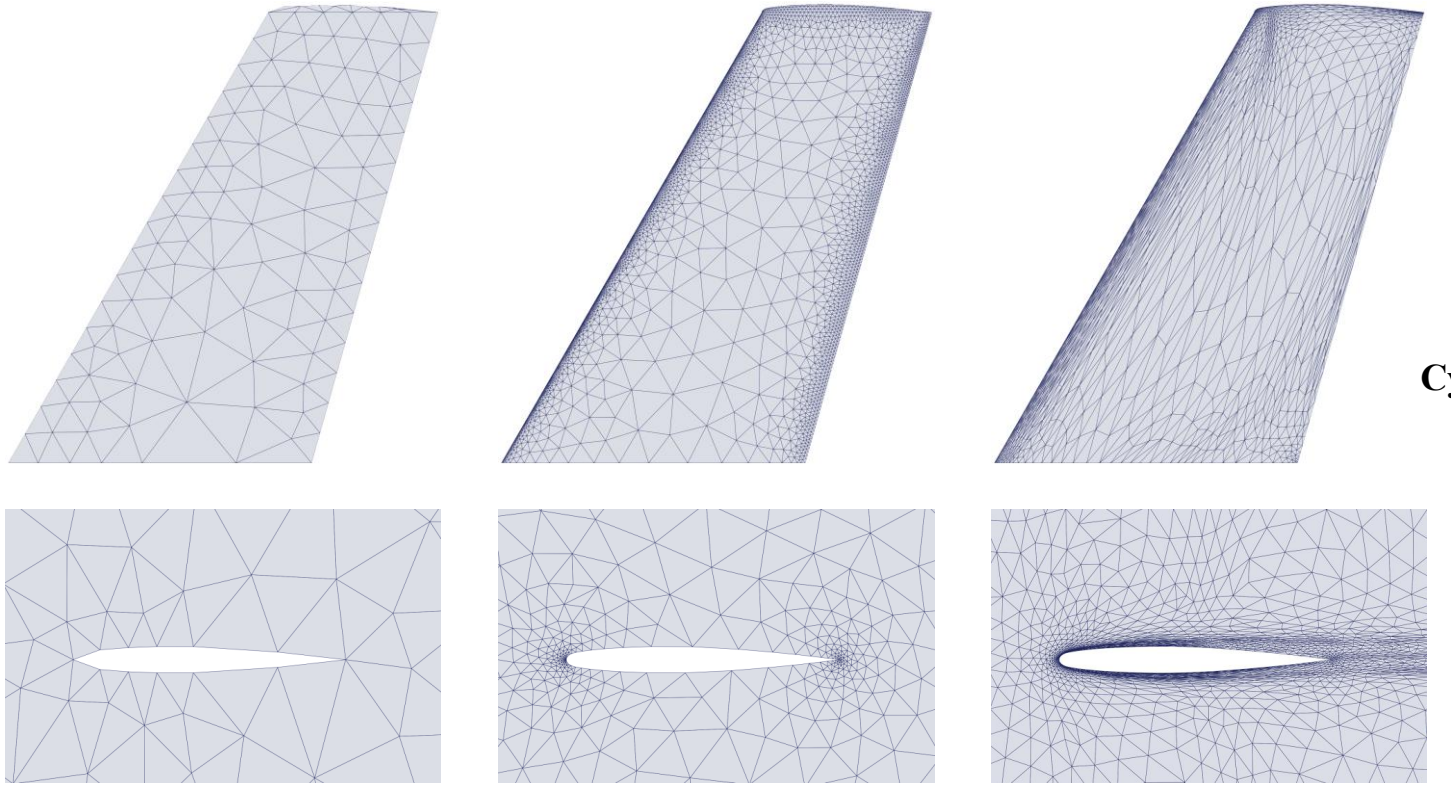


Agent : Initial Mesh input

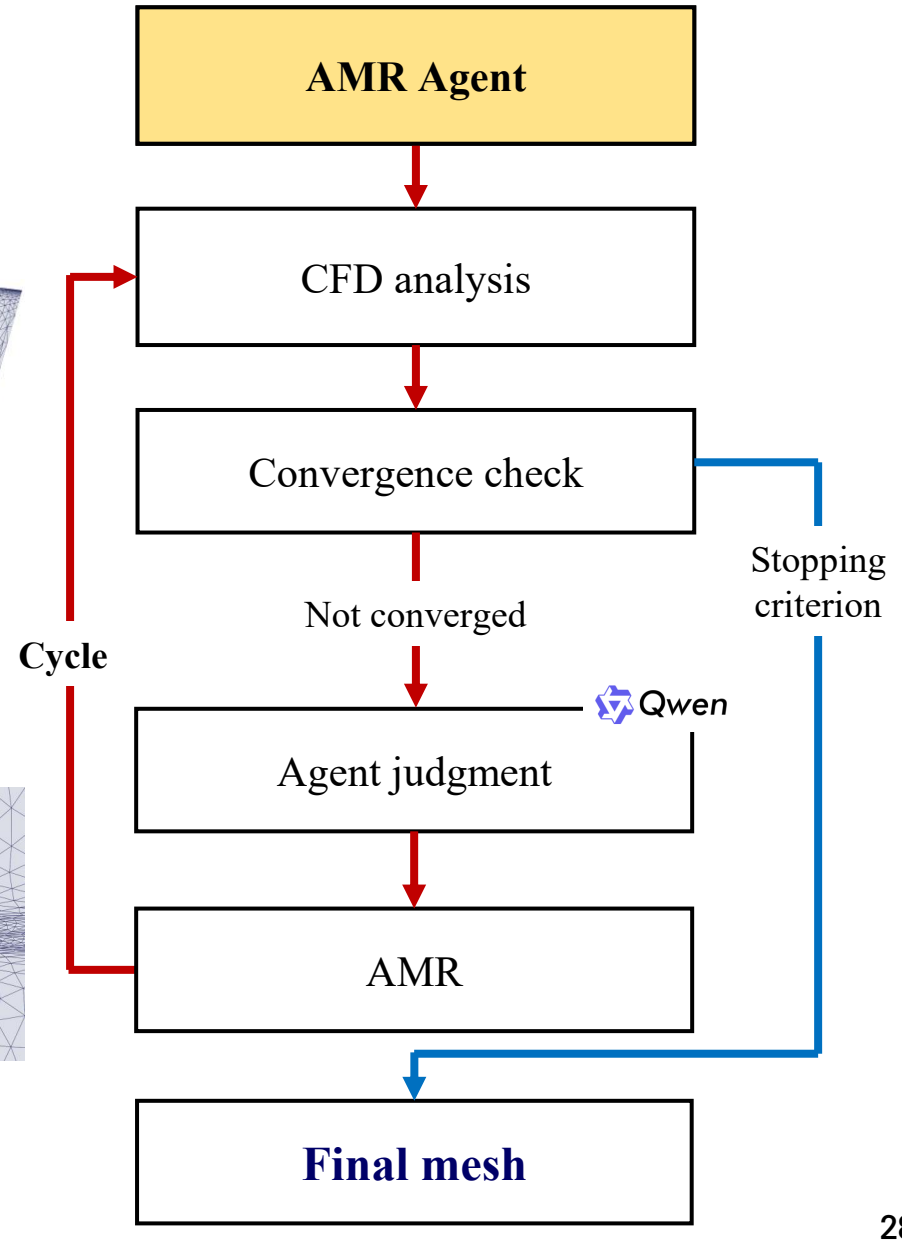
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Different Level mesh

- Level 1부터 3까지 총 3개의 mesh를 agent가 remeshing



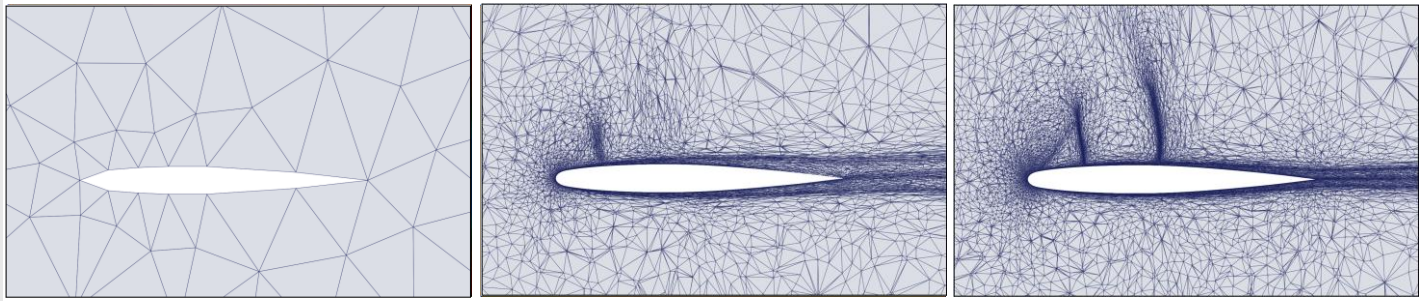
▲ Level 1 (초보자) ▲ Level 2 (중급자) ▲ Level 3 (숙련자)



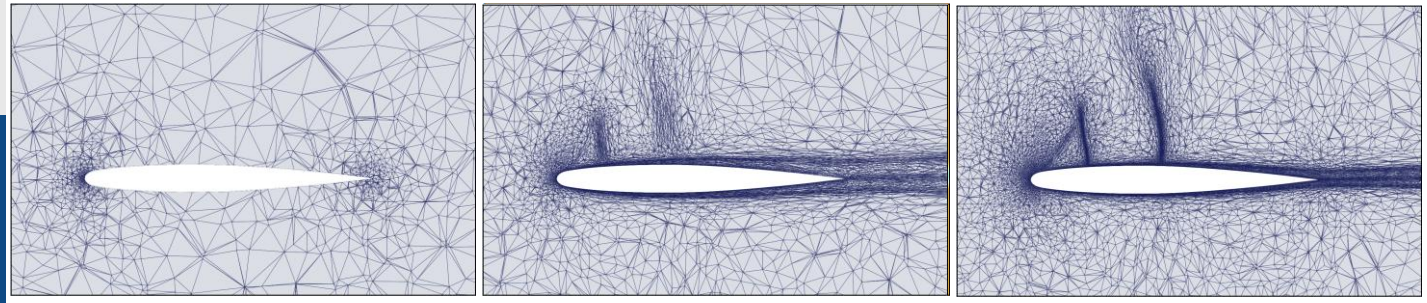
Agent : AMR loop

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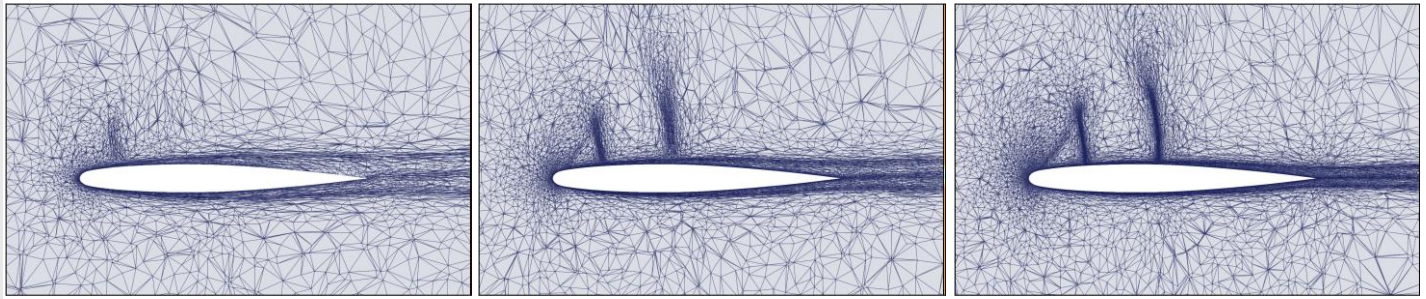
Level 1(초보자) mesh CFD loop

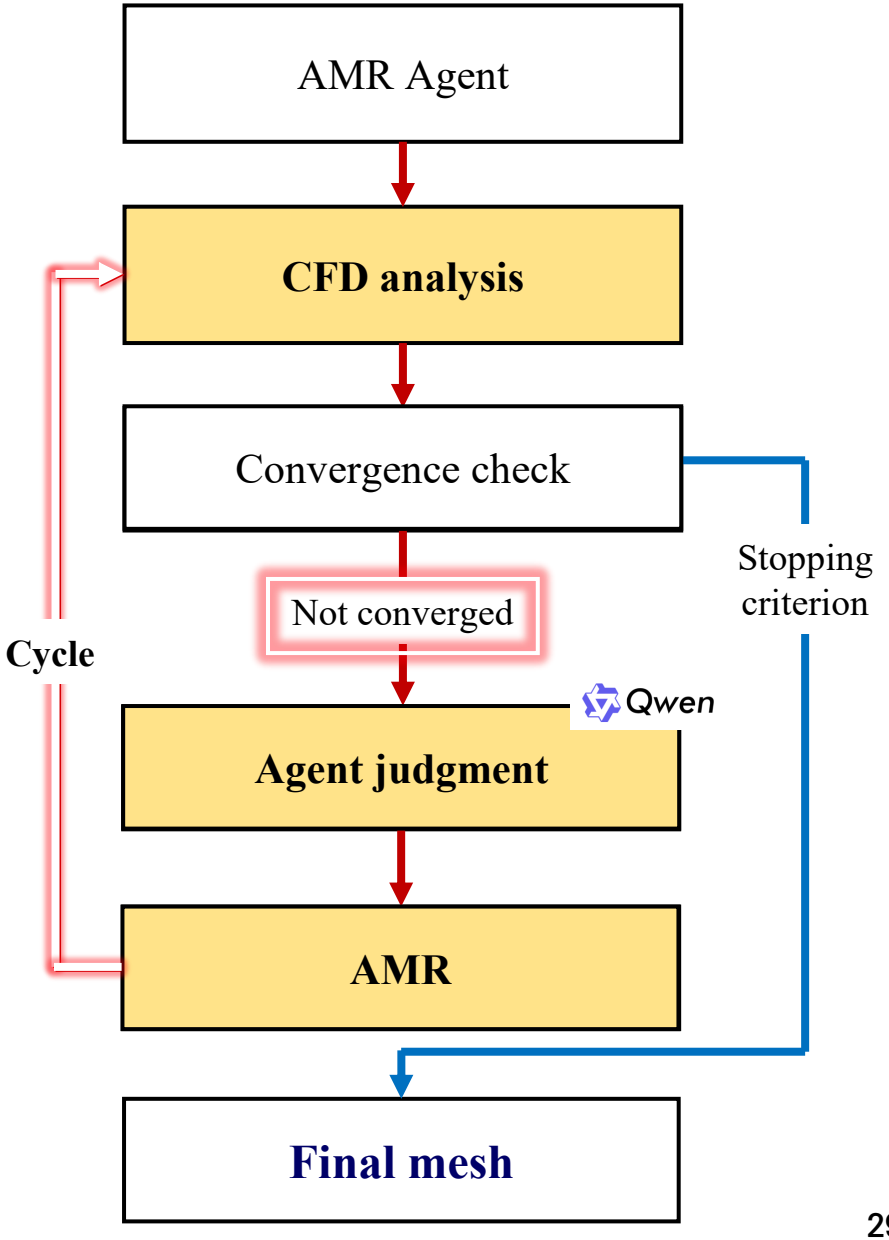


Level 2(중급자) mesh CFD loop



Level 3(숙련자) mesh loop

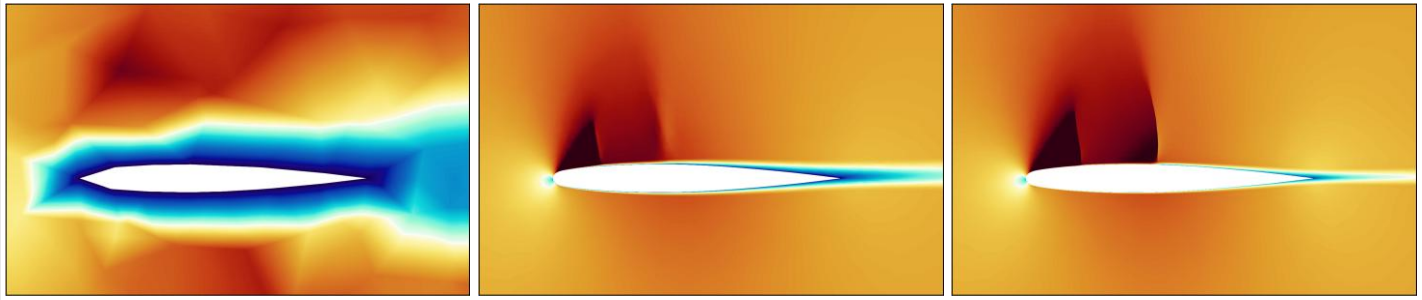




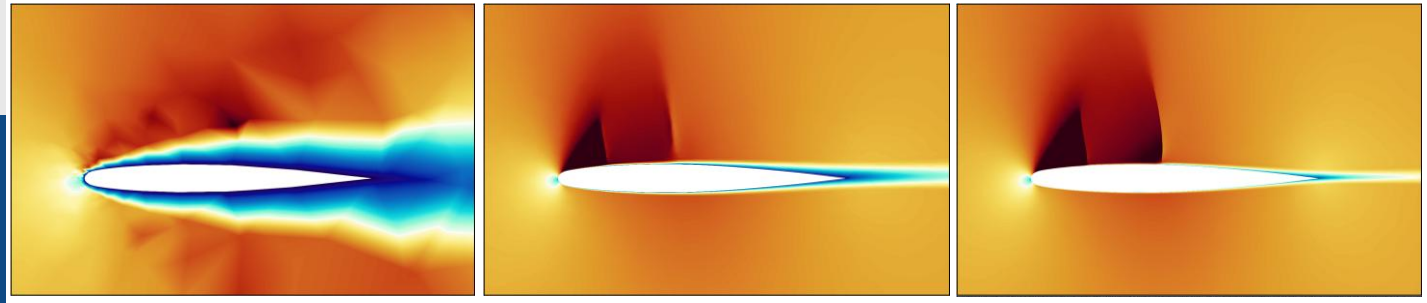
Agent : AMR loop

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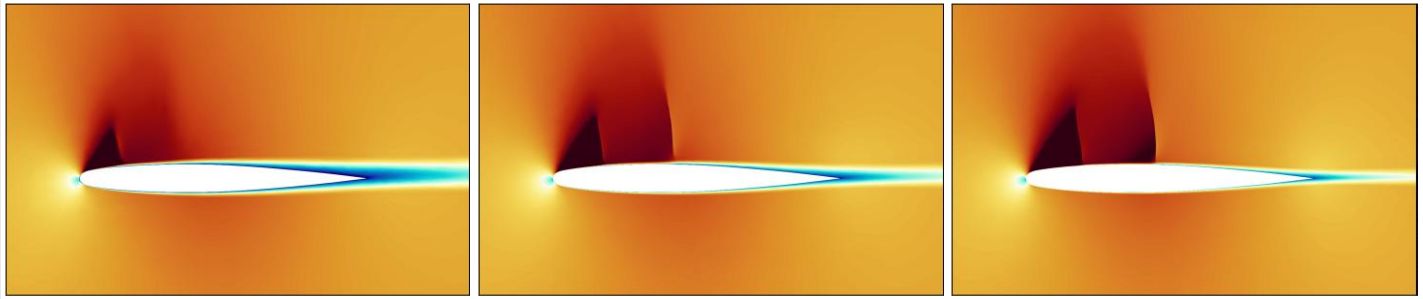
Level 1(초보자) mesh CFD loop

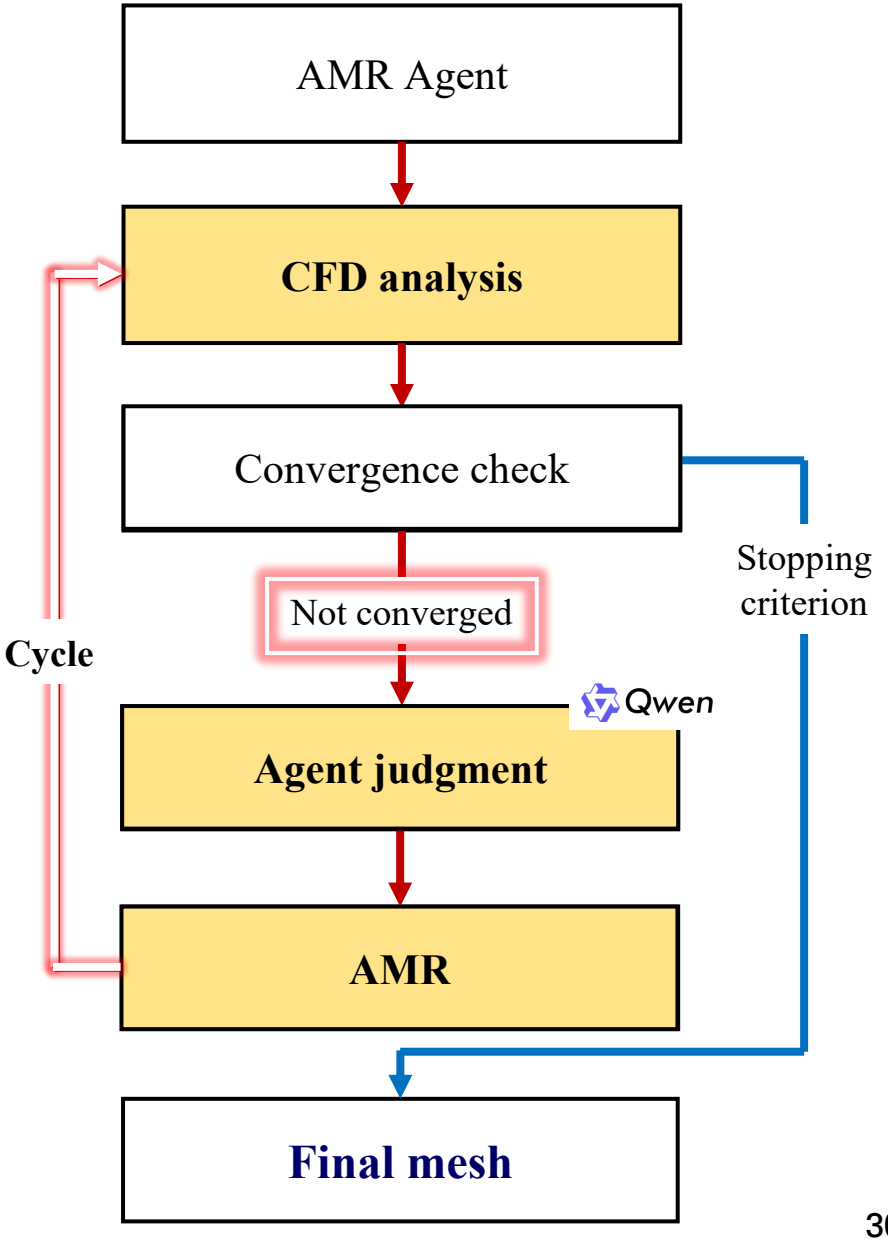


Level 2(중급자) mesh CFD loop



Level 3(숙련자) mesh loop

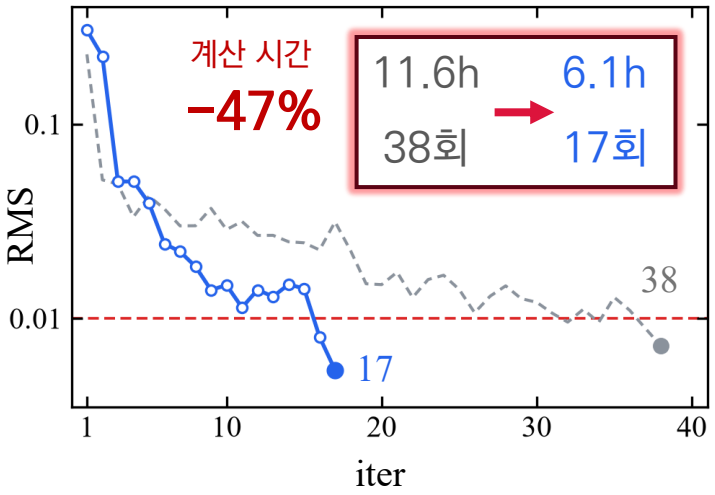


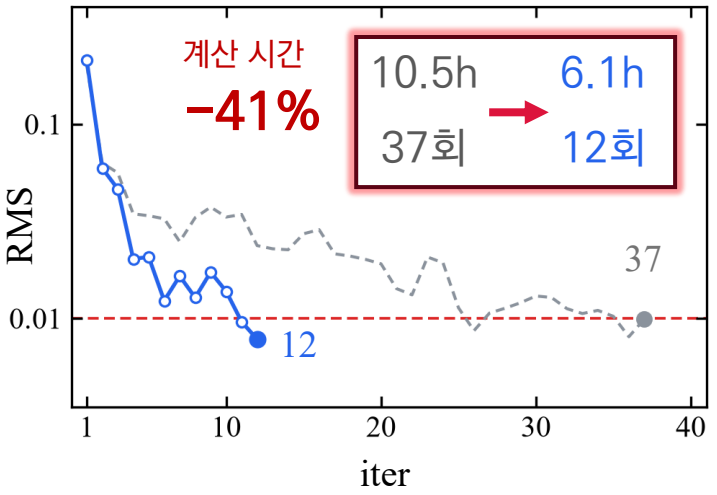


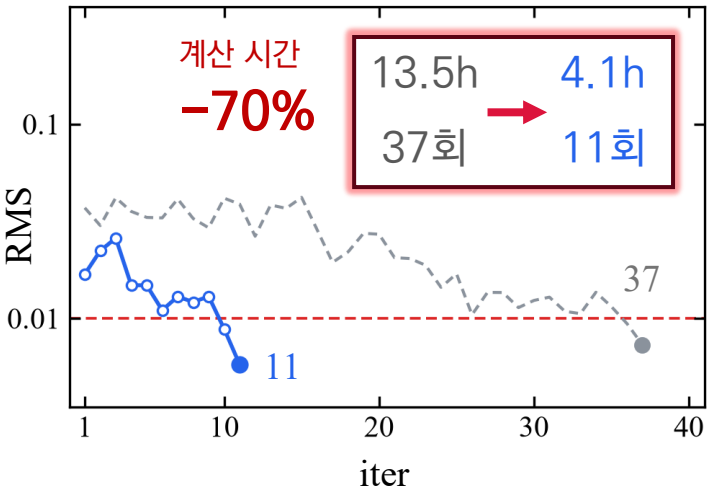
Agent : convergence

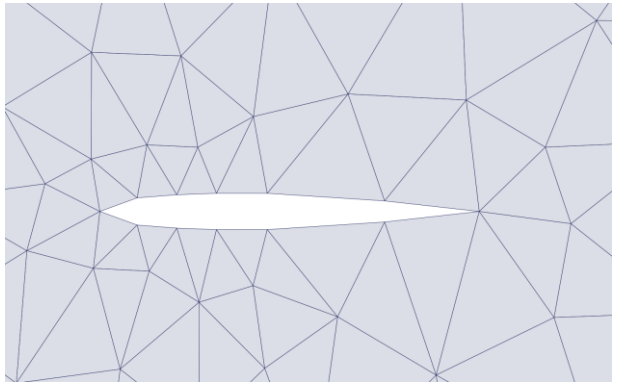
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동일 결과로 수렴하였으나, 반복횟수의 차이 존재

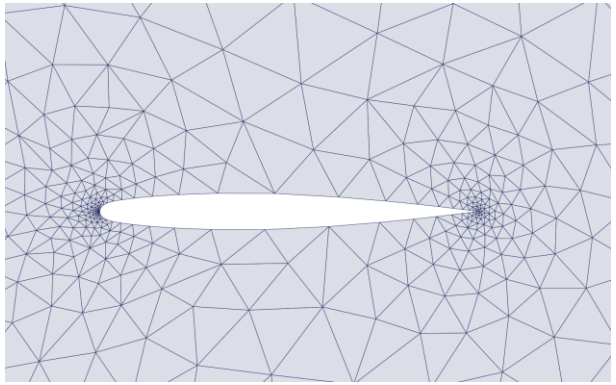




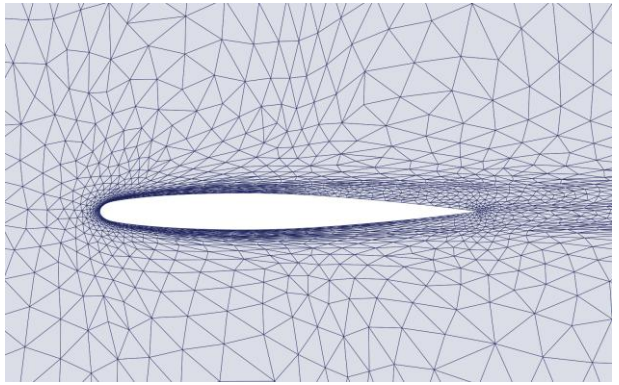




▲ Level 1(초보자)



▲ Level 2(중급자)

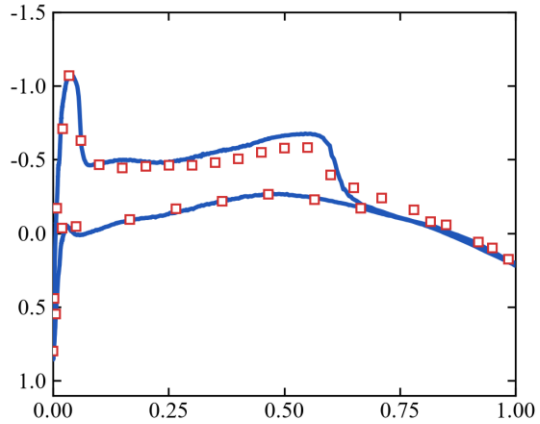


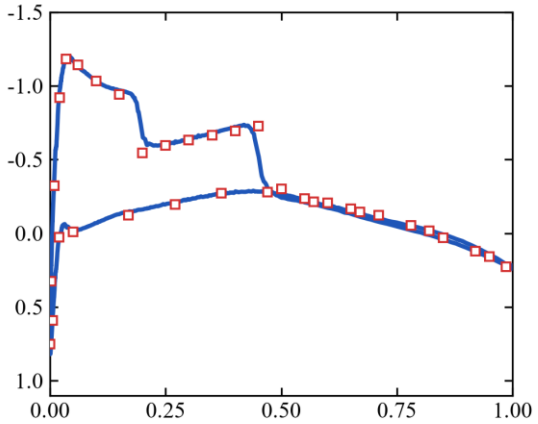
▲ Level 3(숙련자)

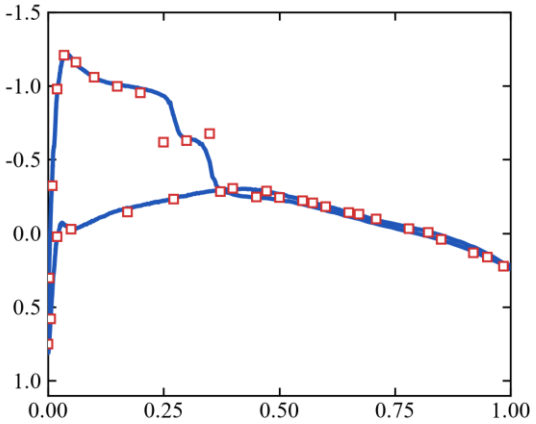
Results

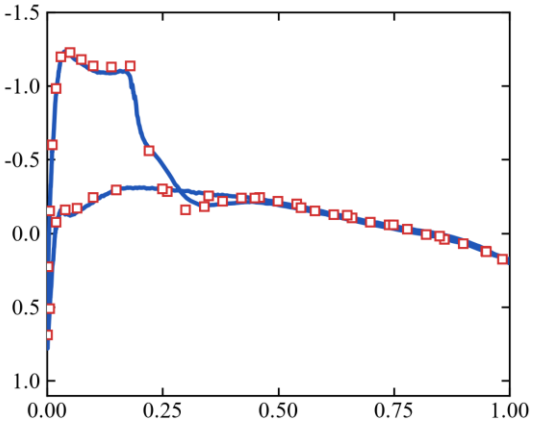
Part 1 Introduction
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Agent CFD vs. NASA CFD









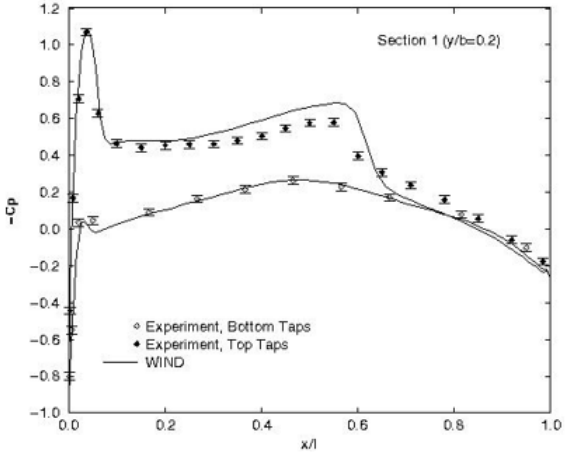


Figure 8. Plot of the pressure coefficients on the wing surface at section 1 (y/b=0.20).

▲ y/b = 0.20

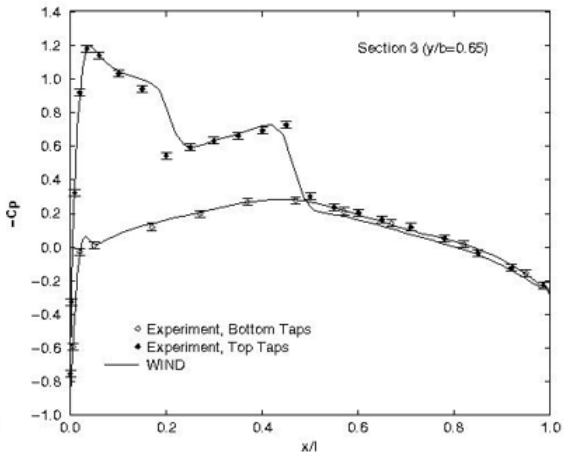


Figure 10. Plot of the pressure coefficients on the wing surface at section 3 (y/b=0.65).

▲ y/b = 0.65

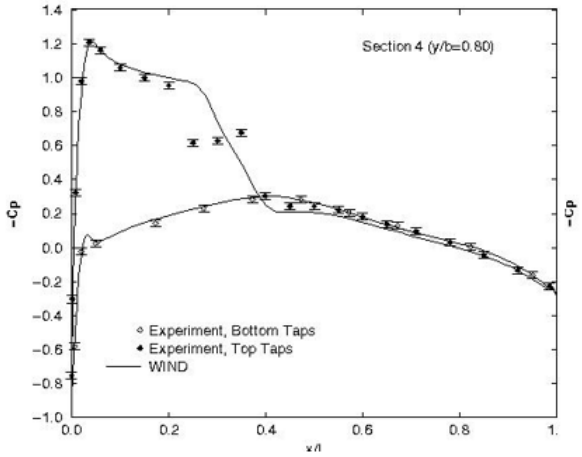


Figure 11. Plot of the pressure coefficients on the wing surface at section 4 (y/b=0.80).

▲ y/b = 0.80

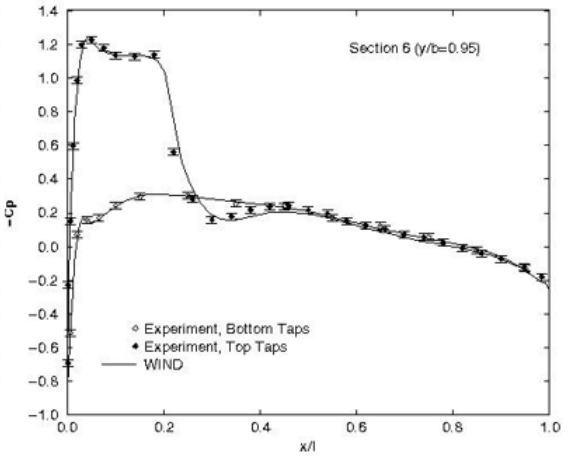


Figure 13. Plot of the pressure coefficients on the wing surface at section 6 (y/b=0.95).

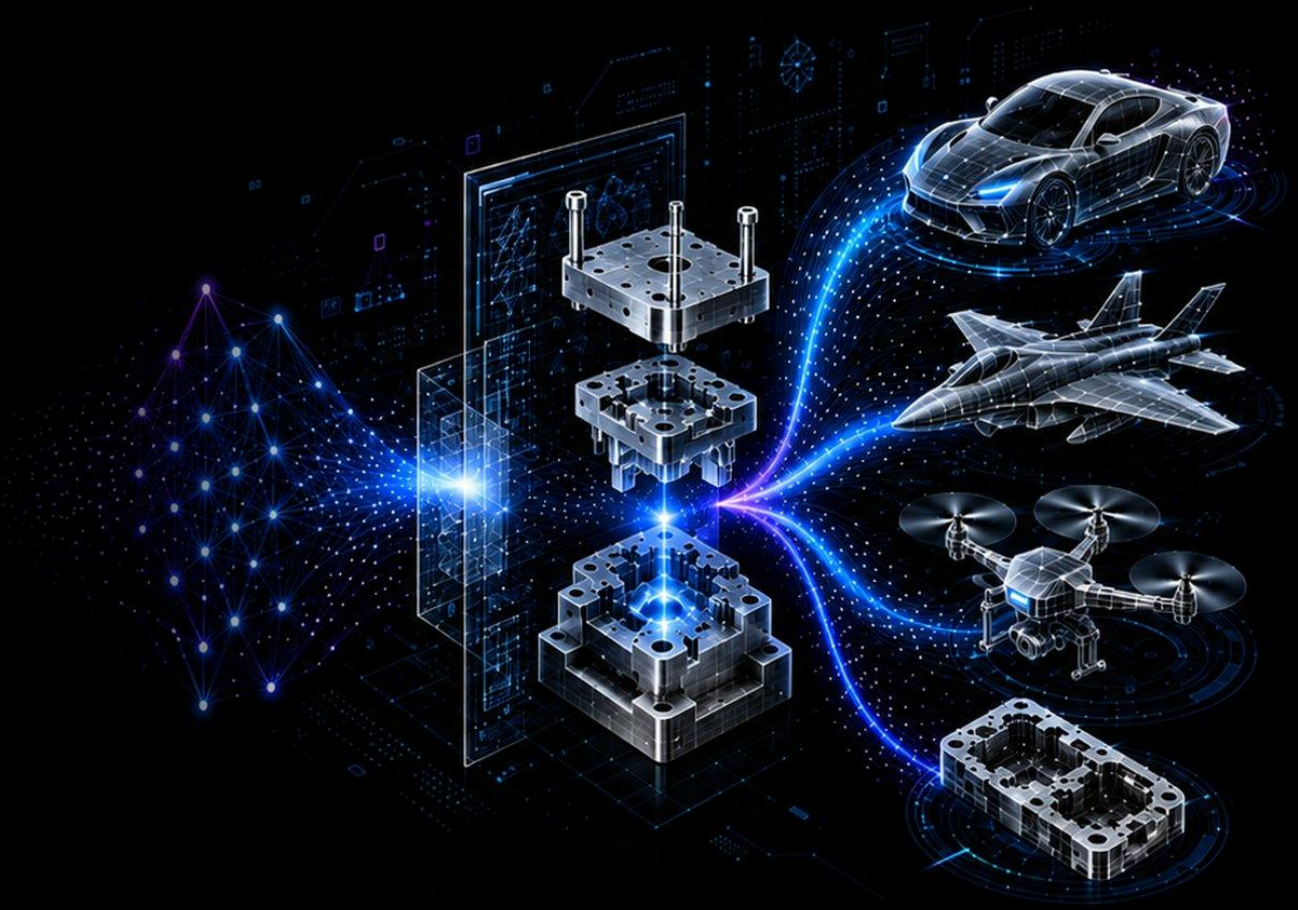
▲ y/b = 0.95

PART

Ⅳ

Conclusion

- Agent DEMO



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Conclusion

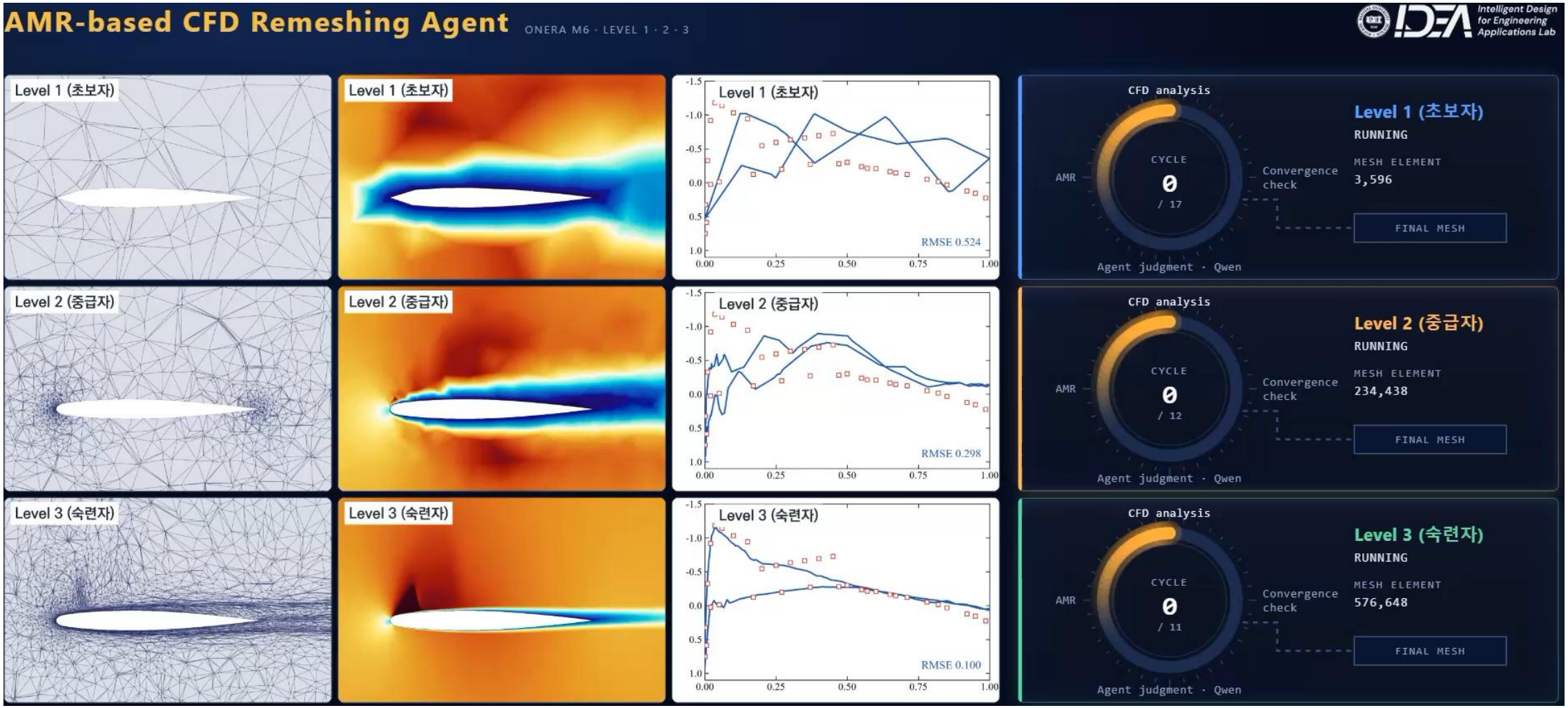
Part 1
Introduction

Part 2
Experiment 1

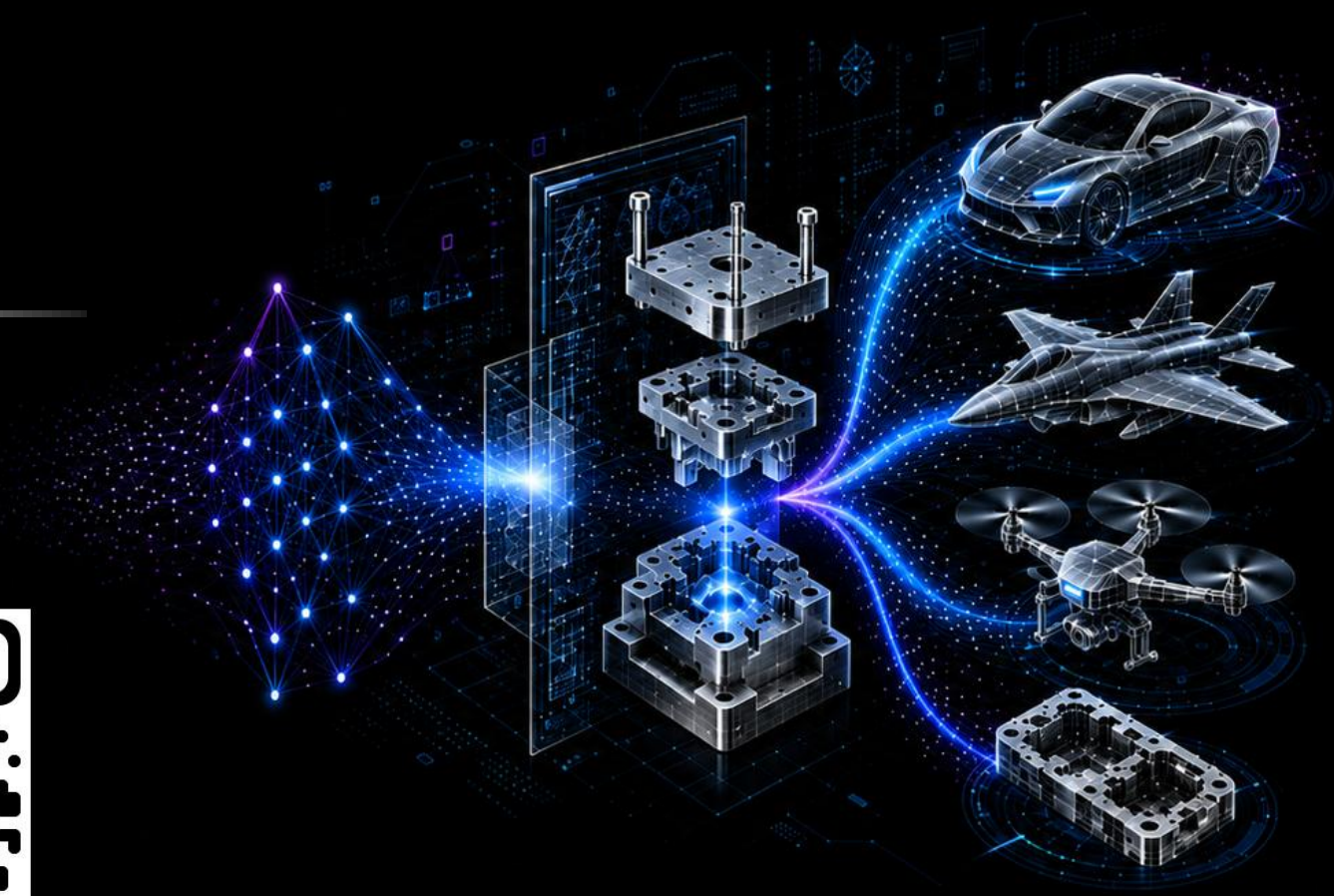
Part 3
Experiment 2

Part 4
Conclusion

AMR-based CFD remeshing agent DEMO



Any Questions?



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