

# 고고도 장기체공 태양광 무인기 프로펠러 개발 사례 소개

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박 동 훈



# HALE UAV

## High Altitude Long Endurance

## Unmanned Aerial Vehicle

- 성층권 고도 장시간 체공
- 감시 / 정찰 / 기상관측 / 통신중계



저비용

운용성

반영구성

친환경





# 국내 HALE UAV 개발

## KARI's HALE UAV Development

EAV-1 (2010)



4.5시간 비행  
Span 2.4m



EAV-2 (2012)

25시간 비행  
Span 11m

22시간 비행  
고도 5km 상승  
Span 6.9m

EAV-2H (2013)



고도 10km 상승  
Twin Prop

EAV-2H+ (2014)





# KARI HALE UAV: EAV-3

## ❖ EAV-3

- Solar cell + Li-Ion Batt.
- Wing Span: 19.5m
- Weight  $\approx$  52.5 kg
- First Flight & 14.2km Climb (2015)
- 18.5 km Climb (2016) (3<sup>rd</sup> in the world)

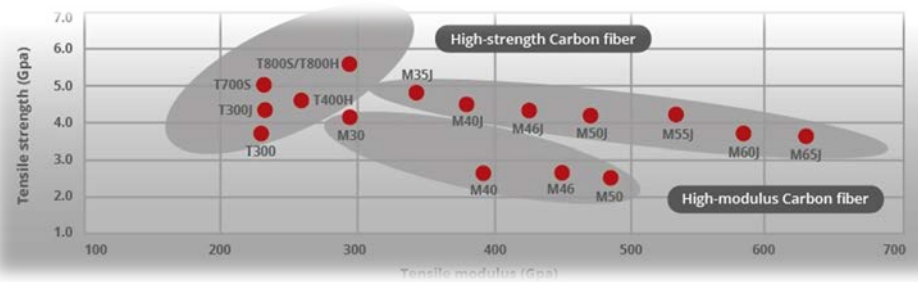
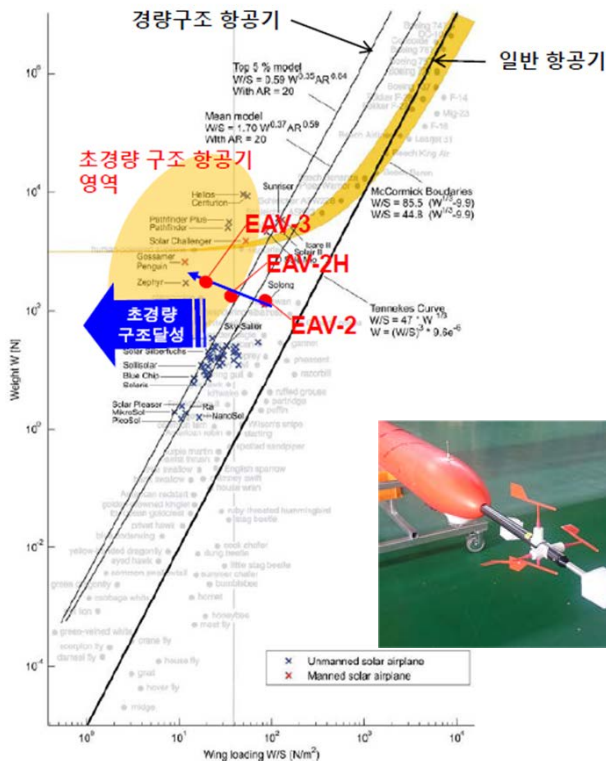


# HALE UAV 개발 기술 이슈

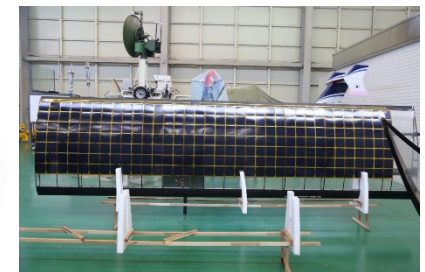
## ❖ 최상위 제약조건

- 초경량
  - 시스템 신뢰도
  - 에너지 효율
- 구조설계, CFRP, Flutter
  - ADS, FCC, Actuators
  - 이차전지, 전기모터, 태양전지

+ **공력효율**



≈



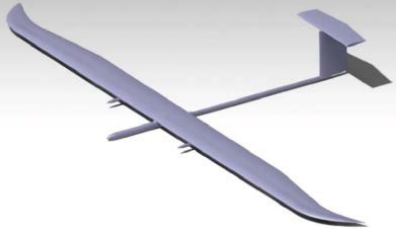
# 고고도 성층권 환경

## ❖ Advantages

- 안정적인 대기 환경
- 높은 태양 에너지 강도 확보 가능

## ❖ Disadvantages

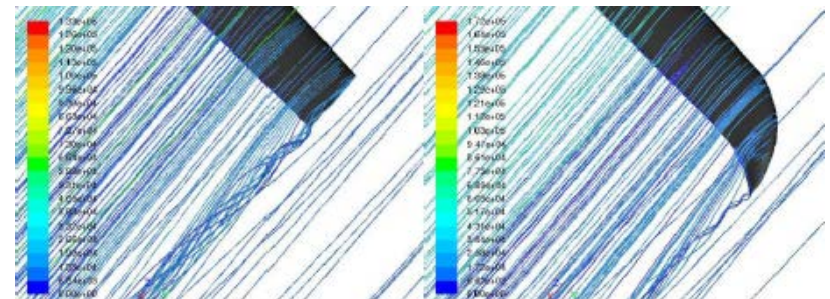
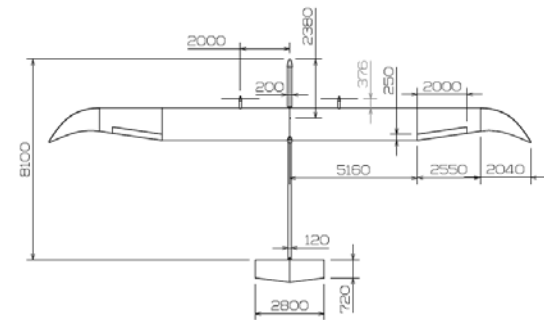
- 희박한 대기 밀도 - 지상의 1/20 수준  
: 양항비 등 공력 성능 저하
- 낮은 대기 온도 - 영하 70도 수준  
: 각종 전자장비, 구동기 신뢰성 문제



## 공력설계

### ❖ 장기체공 목적의 공력성능 확보

- 익형 설계 및 선정 (양항비 최대)
- Planform 설계 (유도항력 최소)
  - : 주날개의 높은 세장비
  - : Raked Wing Tip
- 안정성 확보 및 제약 조건 고려



# HALE UAV 프로펠러

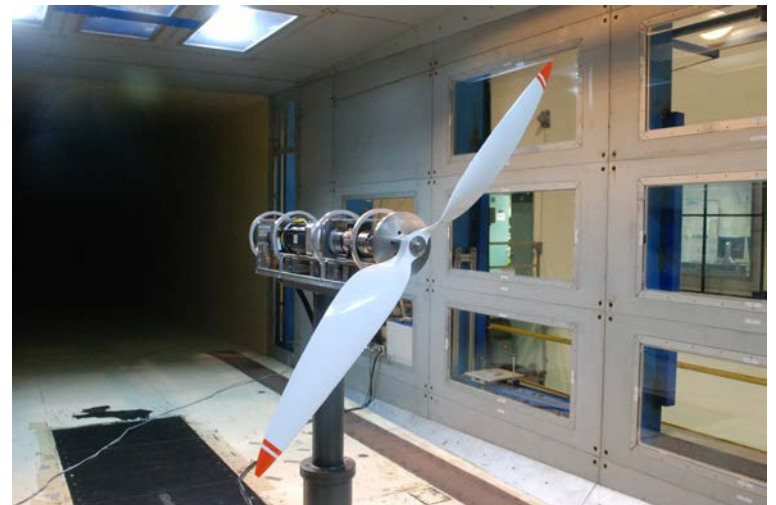
## ❖ 프로펠러 성능 제약 요인

- 고정피치 방식 (초경량, 고고도 환경 신뢰도)  
: 다양한 운용 조건 (지상 → 고고도)
- 블레이드 공력 성능 저하 (고고도)  
: 저레이놀즈수 유동
- 구동모터 성능 제약  
: 지상 - 저회전/고토크  
: 고고도 - 고회전/최대동력

<Variable Pitch>



<Fixed Pitch>



# 프로펠러 특성 및 설계

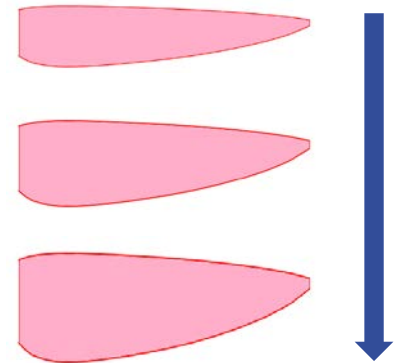
PathFinder



Centurion



- 긴 블레이드 시위 길이  
: 깃 요소 레이놀즈수 확보



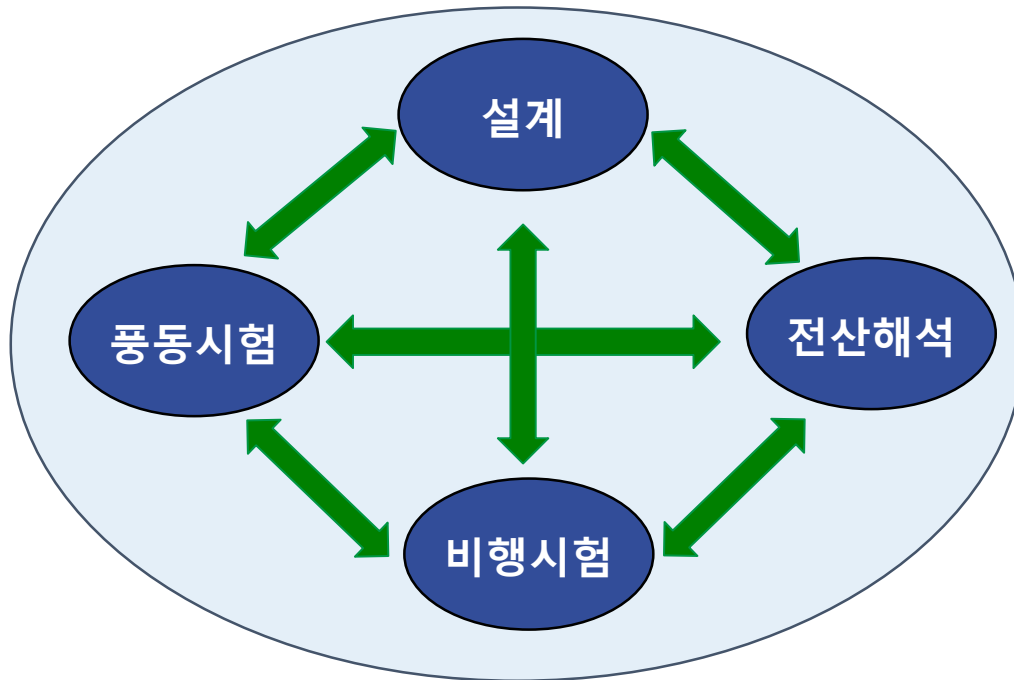
고고도 효율 증가  
& 저고도 토크 증가

## ❖ 프로펠러 설계

- 저레이놀즈수 조건 성능 저하 예측
- 모터 제약조건 / 성능요구 조건 → 최적화



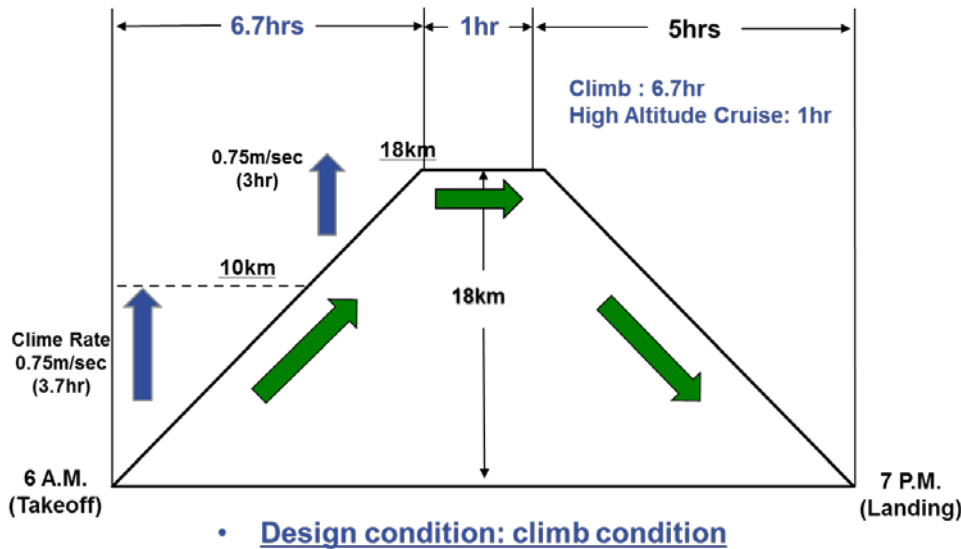
# Work Scope for EAV-3 Propeller



- 저 레이놀즈수 조건 프로펠러 설계
- 성능 획득, 비교 분석
- 설계 기법 타당성 확보
- 전산해석 / 풍동시험 신뢰도 평가
- 저 레이놀즈수 영역 성능 저하 확인

# 설계 요구조건

## ❖ EAV-3 임무형상



## ❖ 운용 요구조건

고도	속도 (m/s)	추력 (N)	
0km	5.8	38.8	← 최대 토크
10km	10.0	26.6	
<u>15km</u>	<u>14.6</u>	<u>21.3</u>	← 설계 조건
18km	18.5	18.8	← 최대 출력

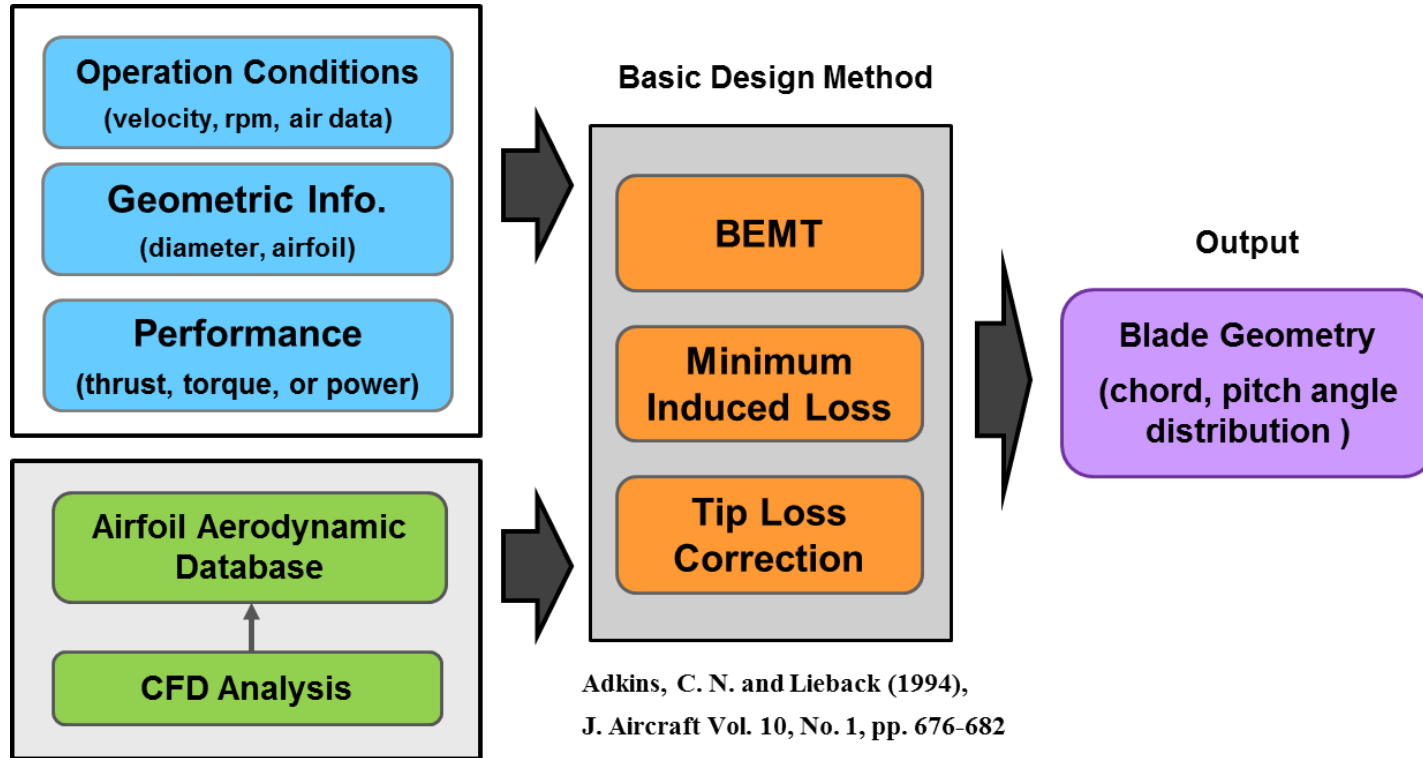
## ❖ 개발 모터 제약조건

- **최대 토크:** 3.8 Nm at 880 RPM
- **최대 출력:** 약 2200 RPM

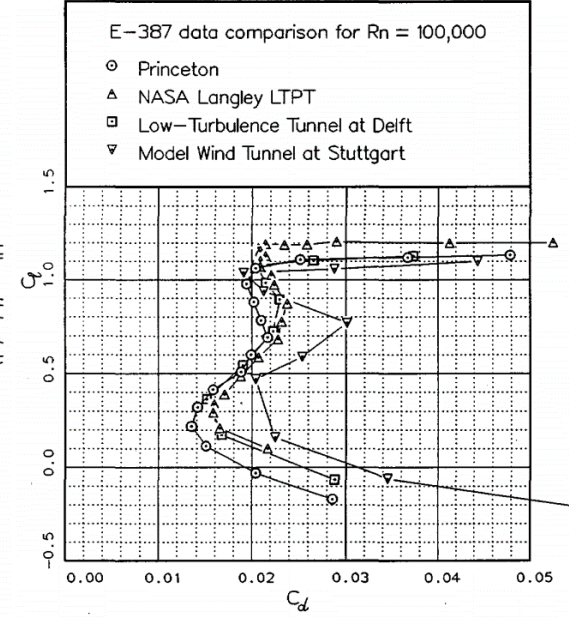
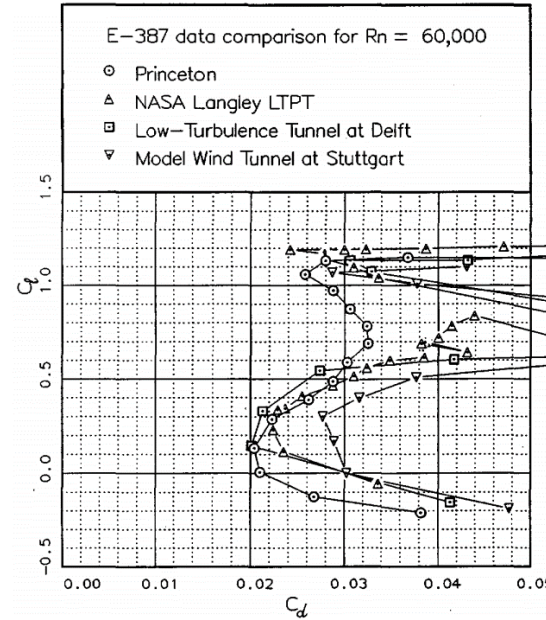
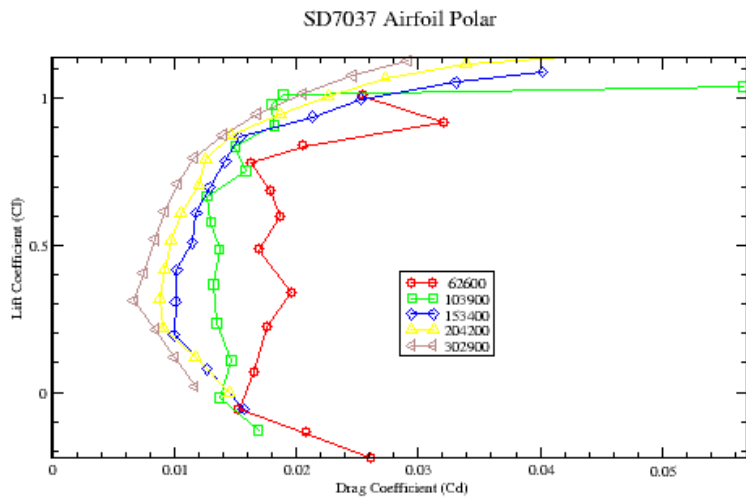
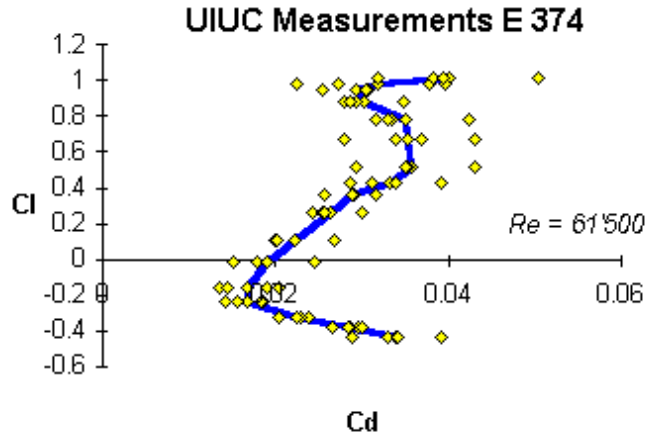
## ❖ 형상 제약조건

- Spinner 직경 16 cm  
(개발 모터의 직경 약 15cm)

# 기본 설계 방법론



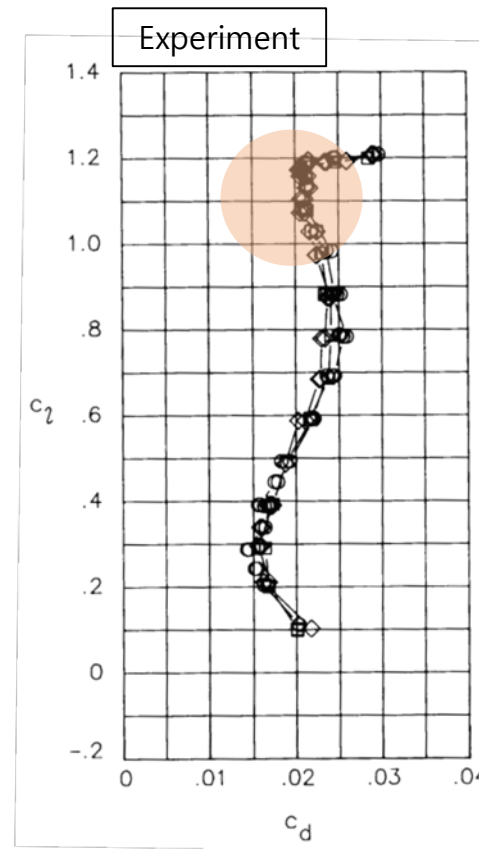
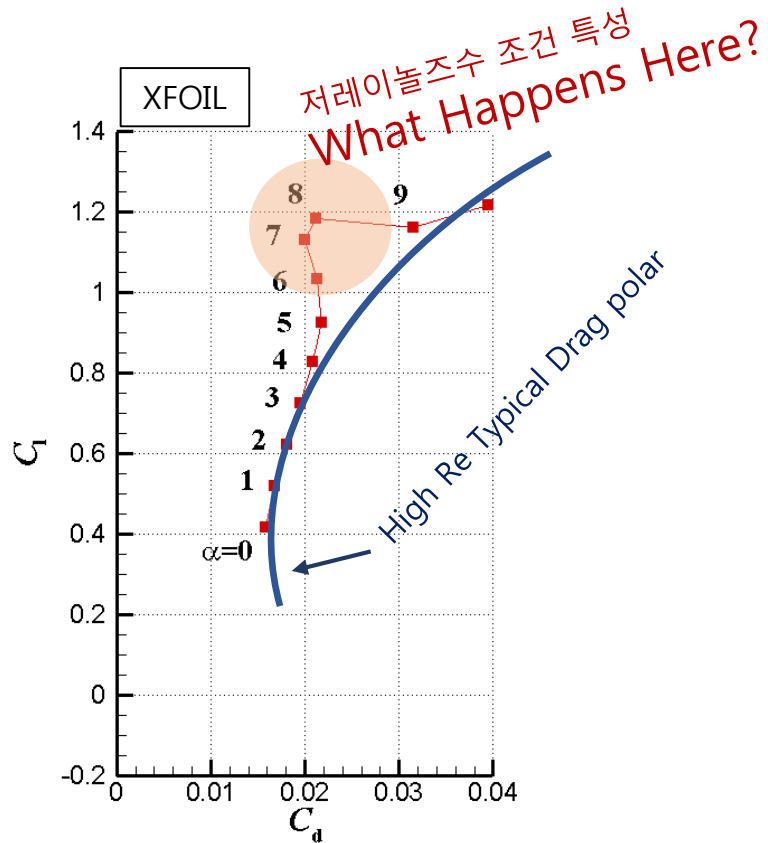
# 저레이놀즈수 익형 공력 성능 (1)



- 풍동시험 - 정확한 측정 자체가 어려움  
(저속 → 속도 및 압력 측정 불확도 급증)
- 레이놀즈수 감소에 따라 drag polar 변화 큼  
drag polar의 형태도 복잡하게 변화

# 저레이놀즈수 익형 공력 성능 (2)

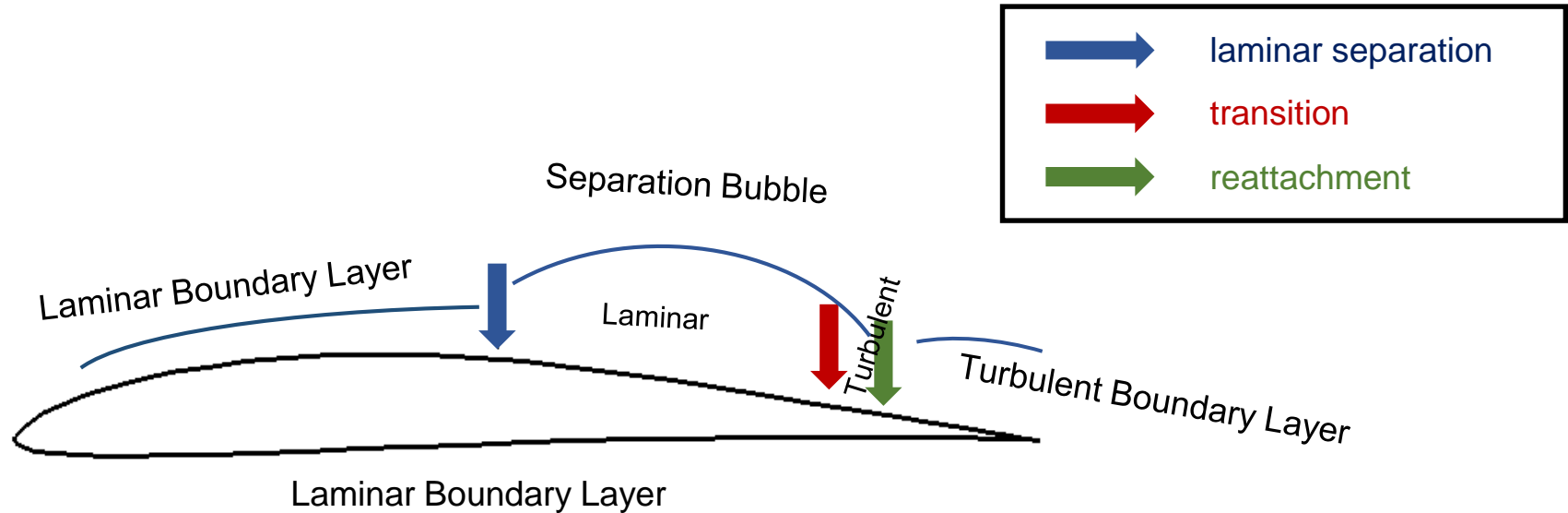
❖ Eppler-387,  $Re=100,000$



McGhee & Walker (NASA TM 4062)

# 저레이놀즈수 익형 유동 특성 (1)

❖ Schematic of Flow Regime - Eppler 387,  $Re_c=100,000$  &  $\alpha=0$

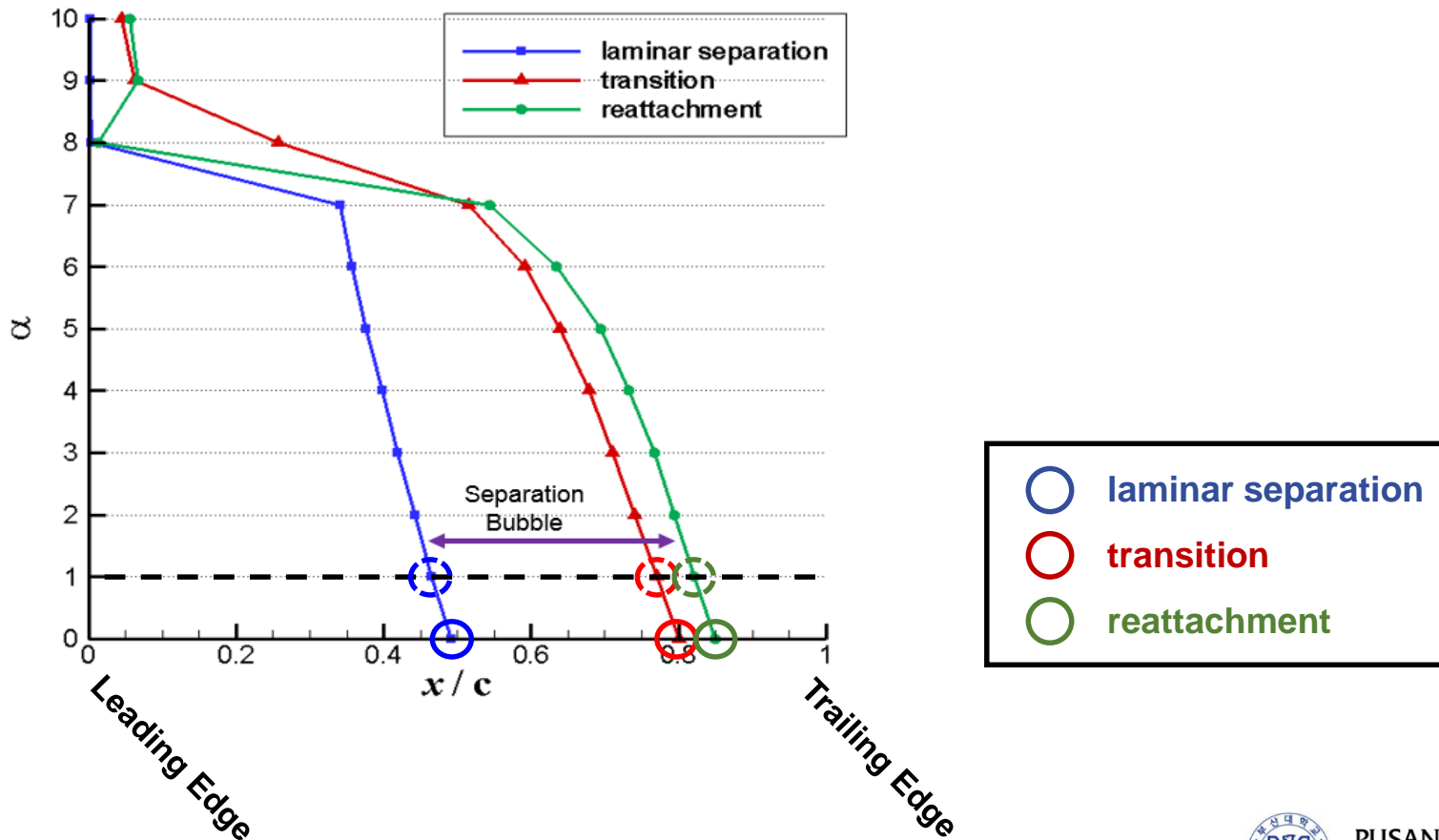


- Suction Side : 층류박리발생 → 박리 기포내 천이 발생 → 천이 후 빠르게 재부착 발생
- Pressure Side : 전구간 층류경계층 유지
- 박리 버블 구간이 길수록 재부착 후의 운동량 두께 증가량이 커져 항력 계수 크게 증가

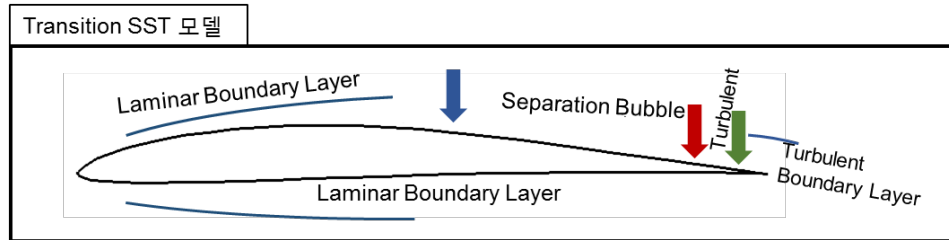
# 저레이놀즈수 익형 유동 특성 (2)

## ❖ Schematic of Flow Regime - Eppler 387, $Re_c=100,000$

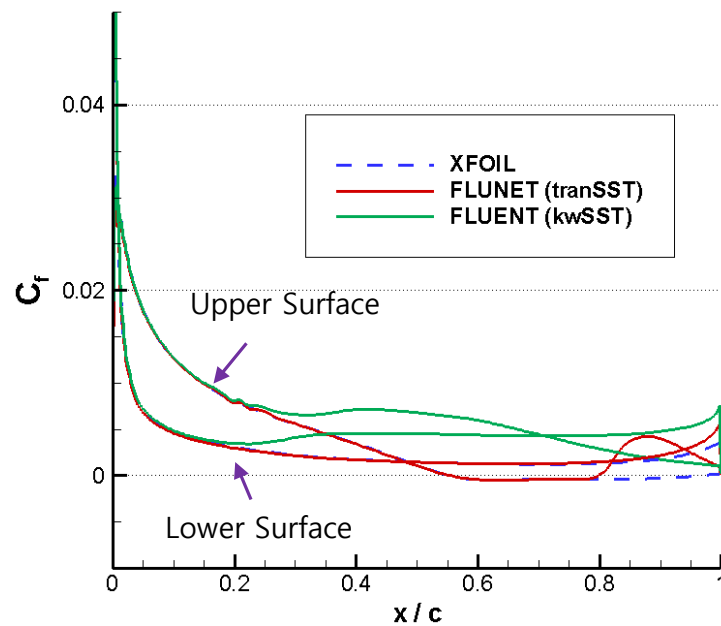
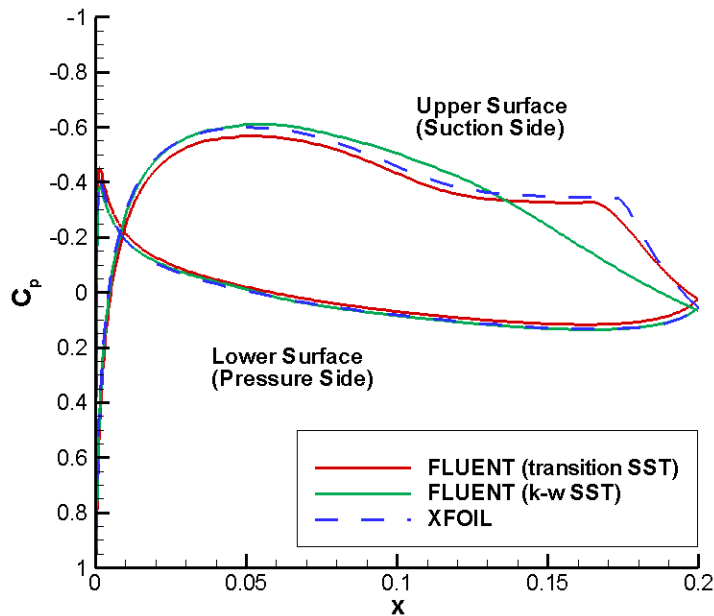
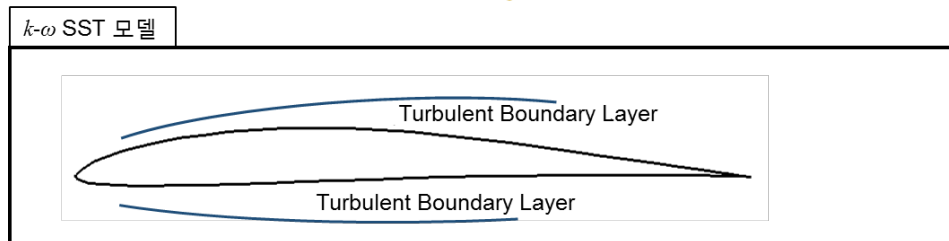
받음각에 따른 Suction Side 층류박리점, 천이지점, 재부착 지점 (XFOIL)



# 저레이놀즈수 익형 공력 데이터



$k-\omega$  SST 모델 ( 2 Eqns. 모델 ) 사용

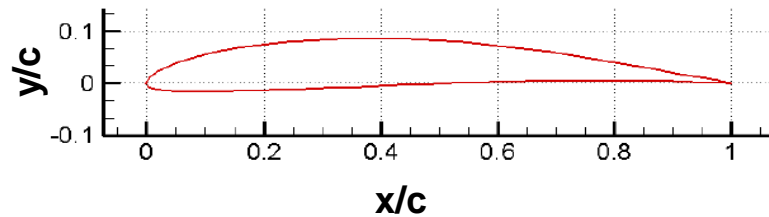




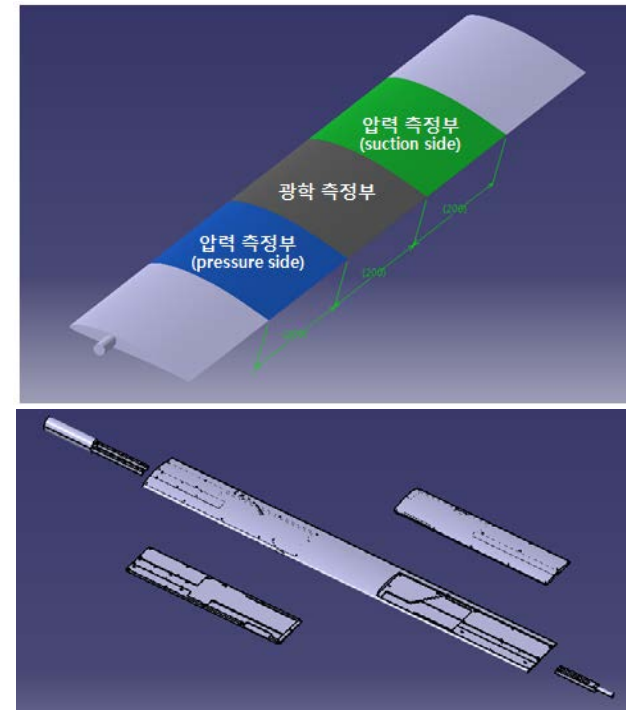
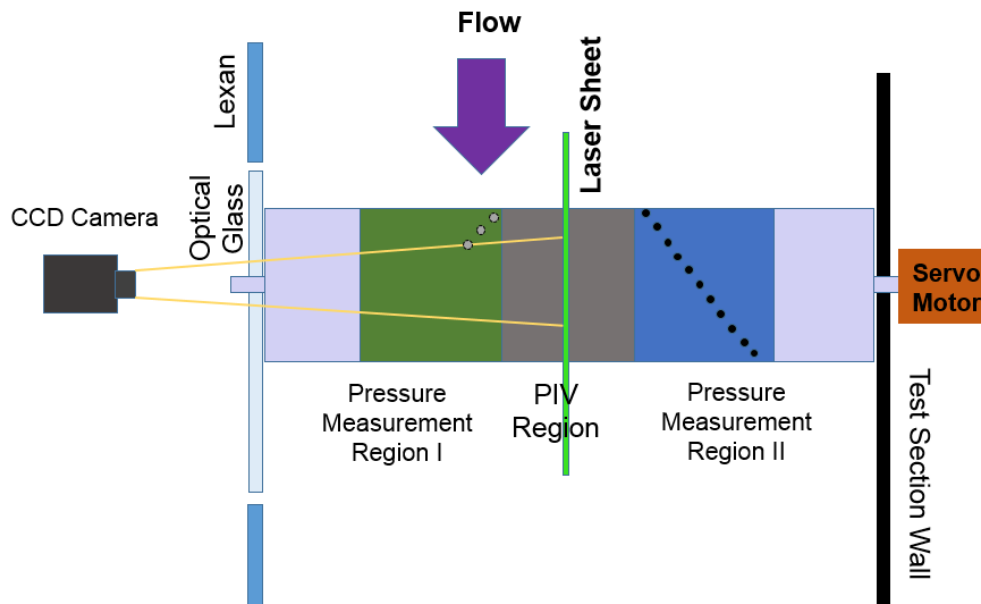
# 저레이놀즈수 익형 풍동시험 (1)

## ❖ DAE-51

- Airfoil Chord Length : 150 mm

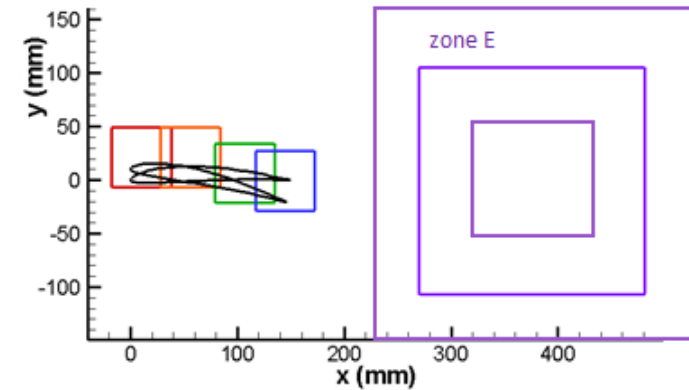
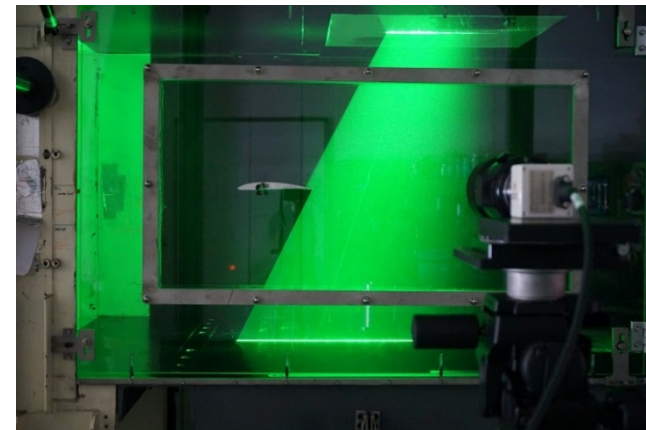
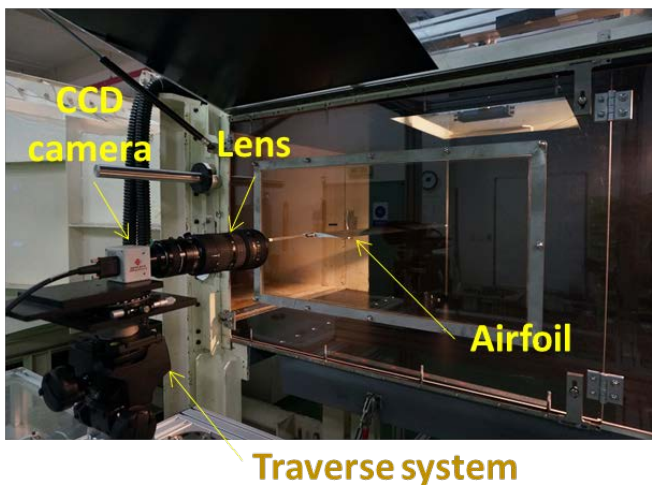
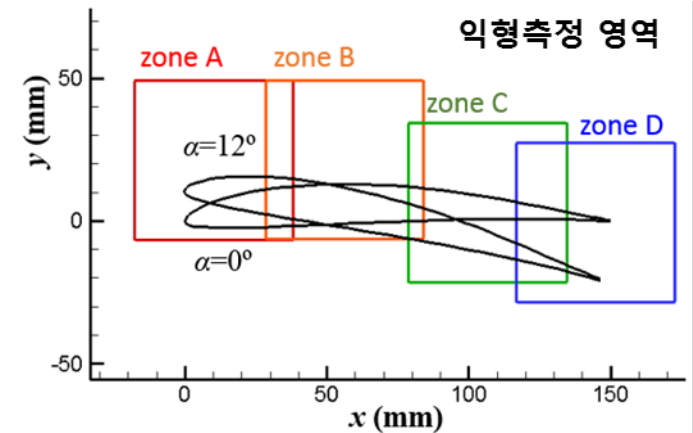
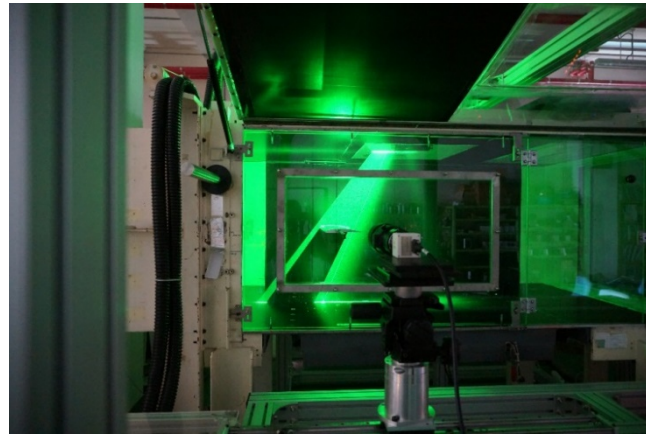
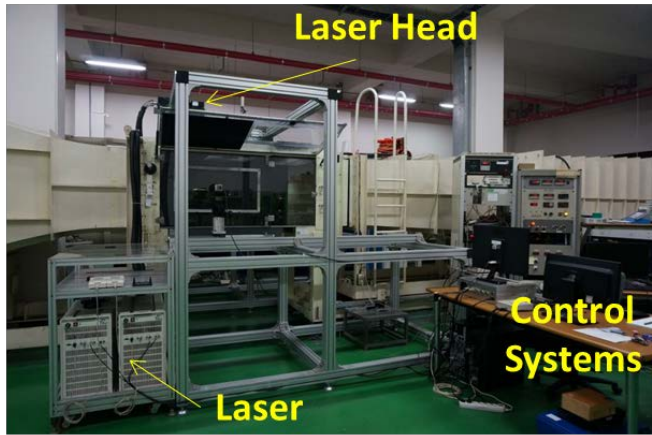


Reynolds No.	Wind Speed	$Q_c$
100,000	9.7 m/s	58 Pa
80,000	7.79 m/s	37 Pa
60,000	5.84 m/s	21 Pa



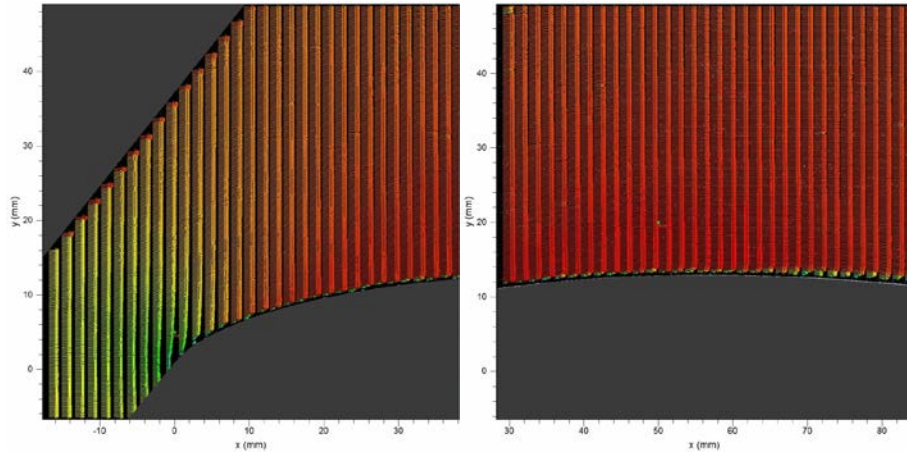
# 저레이놀즈수 익형 풍동시험 (2)

❖ 저레이놀즈수 유동: 익형 표면 압력 측정 / 경계층 및 후류 유동장 광학 측정 (PIV)

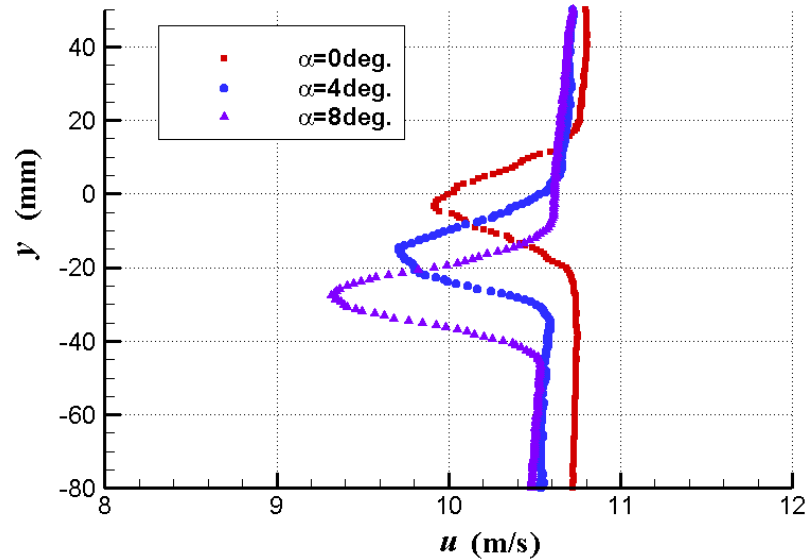
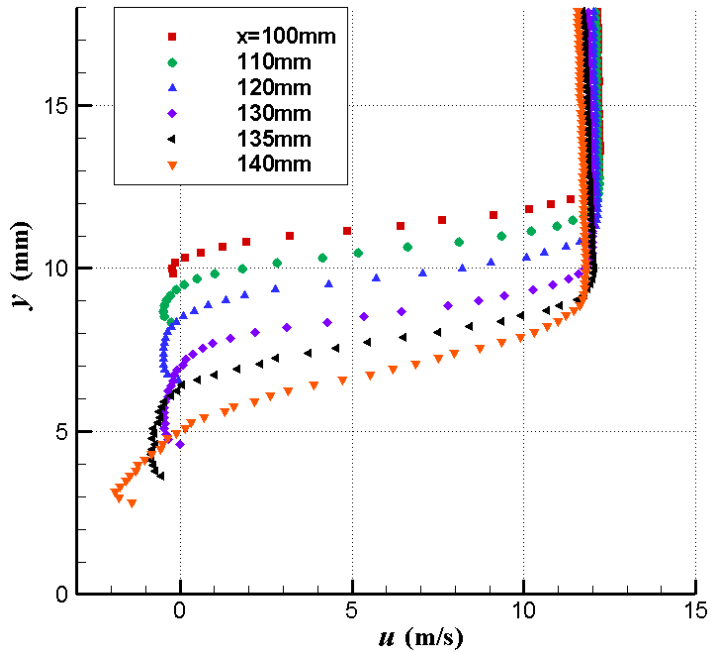
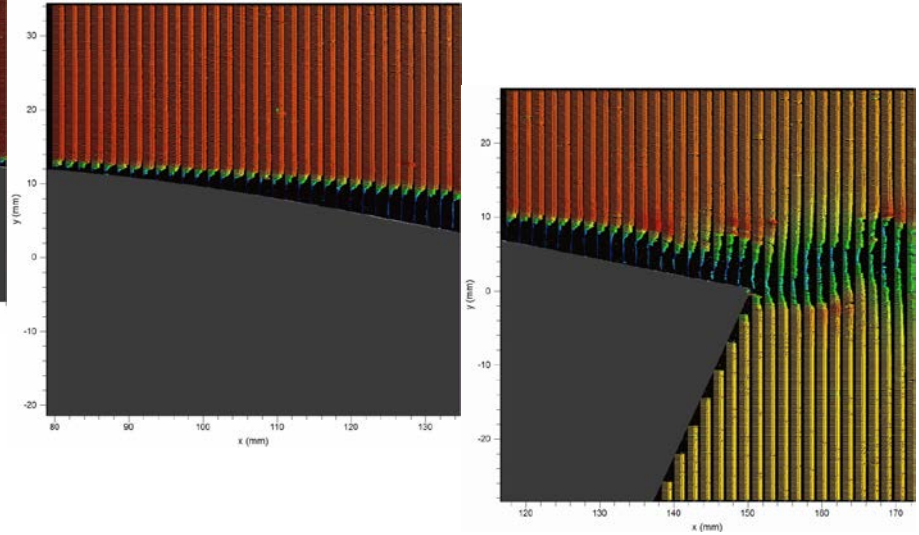


- 2Hz로 50 Pair의 이미지 획득 후 처리

# 저레이놀즈수 익형 풍동시험 (3)



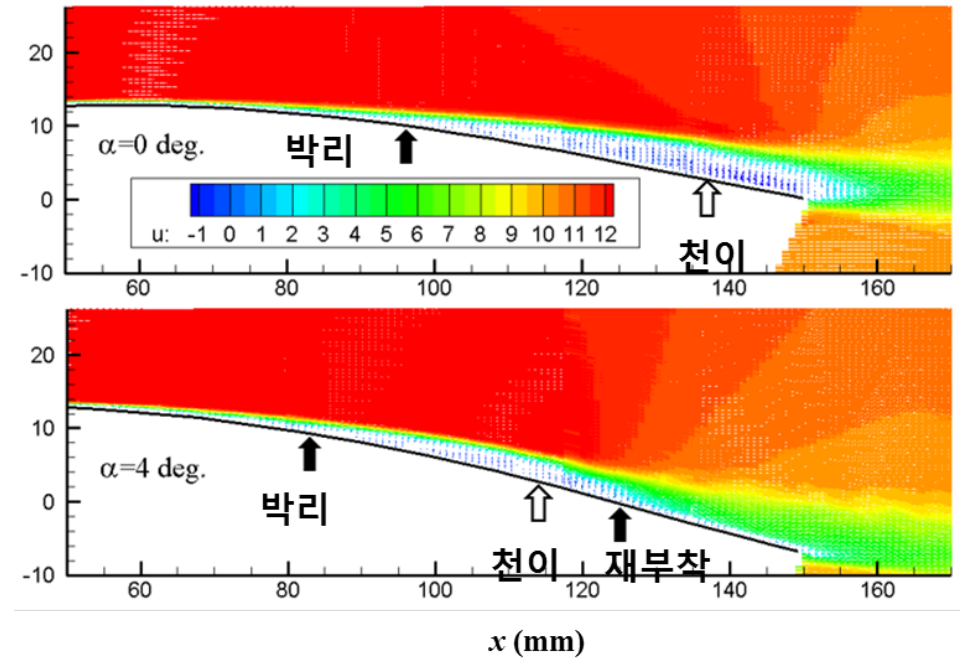
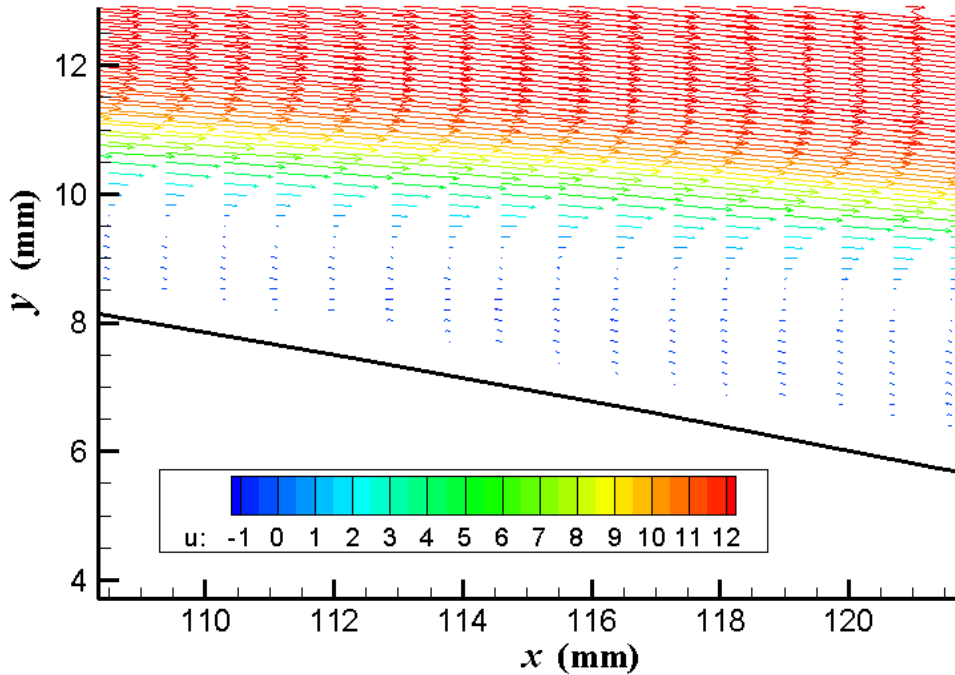
## ❖ PIV Results



# 저레이놀즈수 익형 풍동시험 (4)

## ❖ PIV Measurement Results

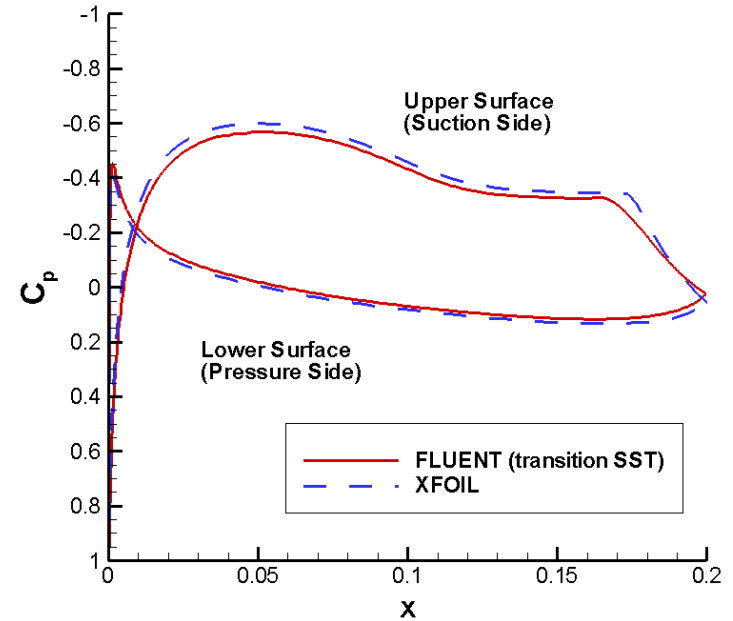
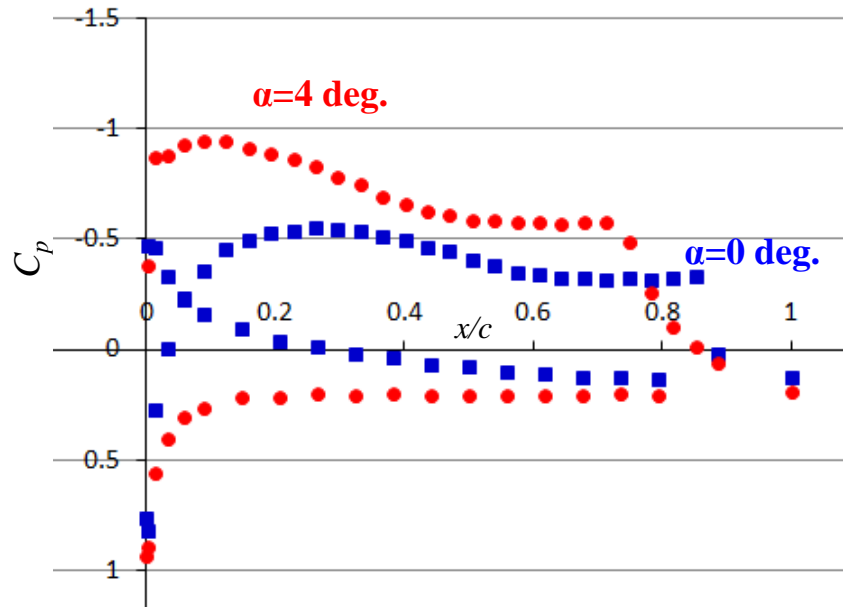
- Example:  $Re_c=10^5$ ,  $\alpha=0$ , zone C



- 경계층 프로파일 및 박리 / 층류, 난류 경계층 특성 파악
- 후류 속도 프로파일의 특성을 파악

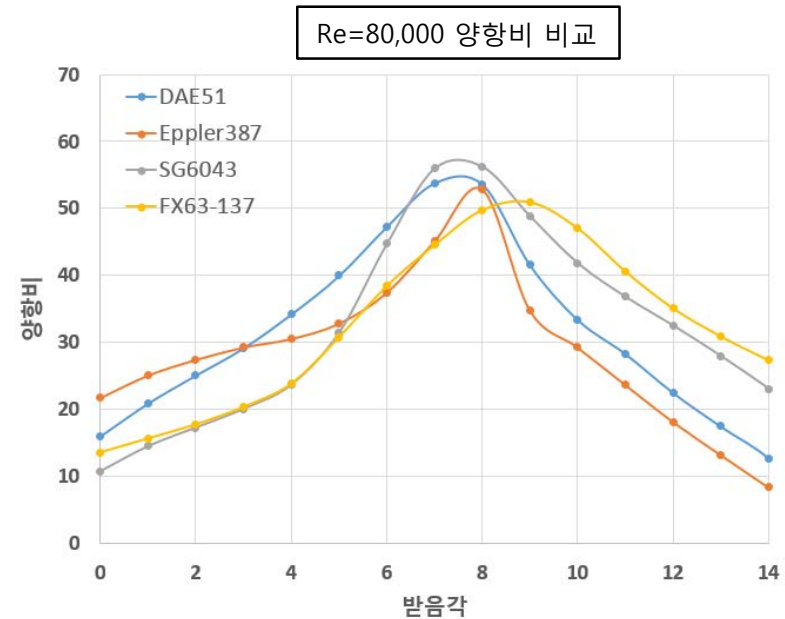
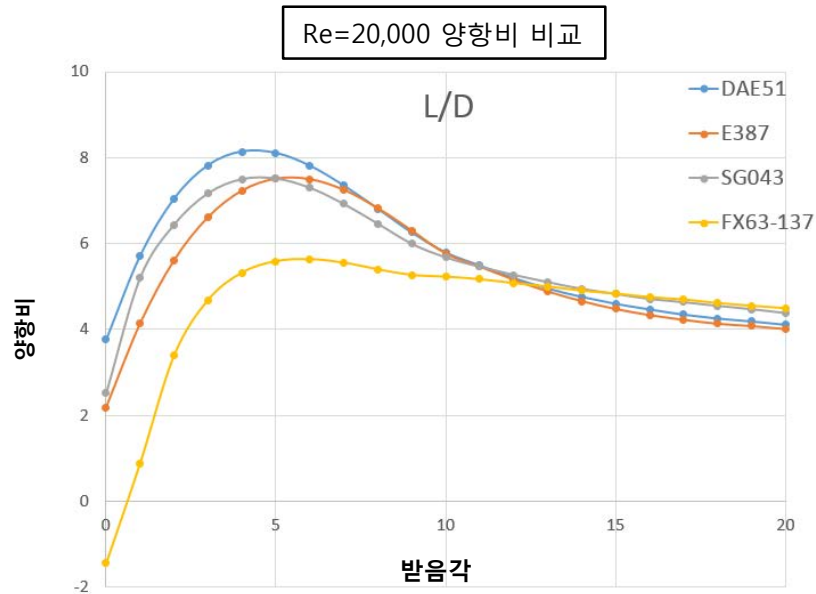
# 저레이놀즈수 익형 풍동시험 (5)

## ❖ Pressure Measurement Results



- Pressure Systems – DTC Initium 4 inch H<sub>2</sub>O

# 블레이드 익형 선정

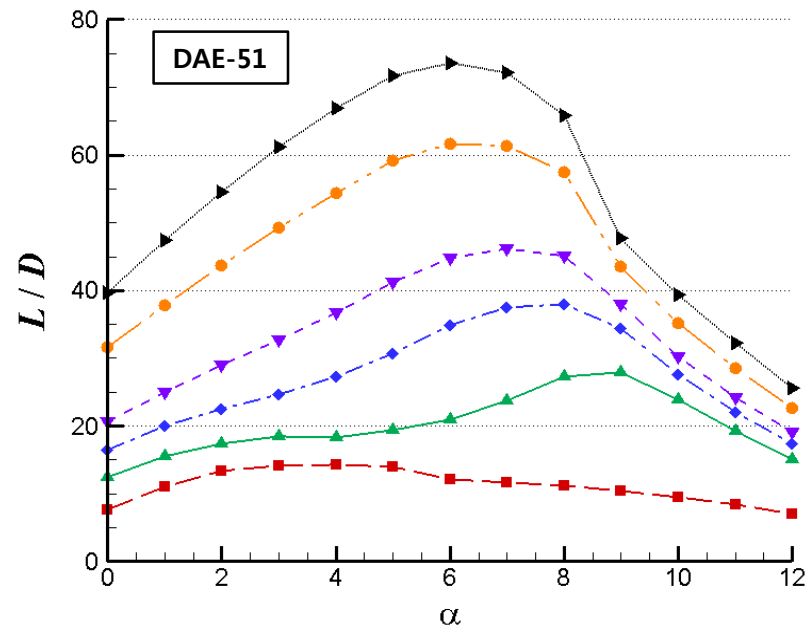
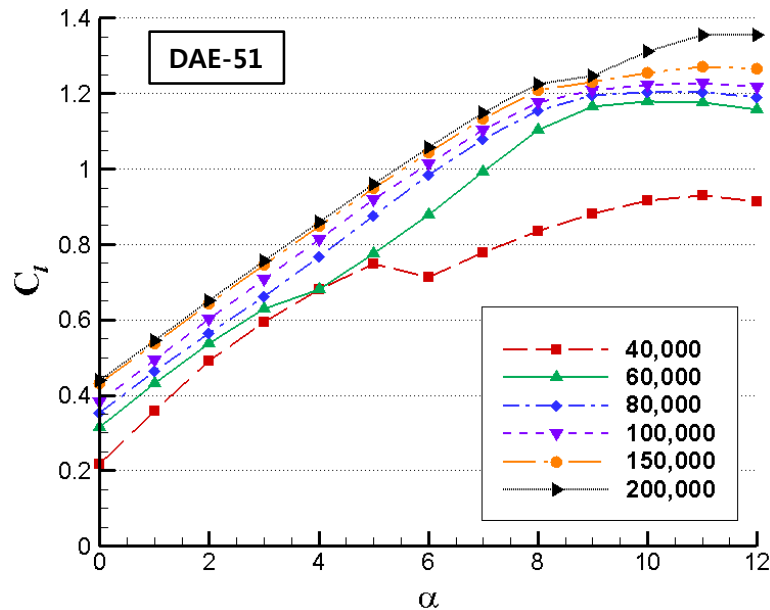


- **DAE-51** : 실속 이전의 주 사용 받음각 ( $C_l=0.5\sim 1.2$ )에서 양항비가 가장 우수한 것으로 판단

# 익형 공력 DB 생성

## ❖ 익형 공력 데이터

- BEMT에 필요한 익형 공력 DB: CFD를 사용하여 생성
- FLUENT v13 / 2차원 비정상 해석 / transition-SST 모델 / C-Type 정렬 격자 ( $y^+ \sim 1$ )
- 레이놀즈수: 10,000 ~ 100,000 까지 10,000 간격



# 설계 Tool 개발 (1)

## ❖ KARI-Prop

- Source code for propeller design based on C++
- Construction of GUI based on MFC

Design Window

The screenshot shows the 'Overall Design' window with the following sections and values:

- Geometry:**
  - Number of Blades: 2
  - Number of Blade Elements: 50
  - Propeller Diameter (m): 1.0000
  - Spinner Diameter (m): 0.1000
- Operating Condition:**
  - Velocity (m/s): 15.00
  - RPM: 1500.00
- Design Method:**
  - Thrust (N): 40.0000
  - Torque (Nm): 4.5926
  - Power Required (W): 721.4117
  - Power Out (W): 600.0000
  - Efficiency: 0.8317
- Section Airfoil / Cl Distribution:**
  - Airfoil: NACA 2412
  - Database:  XFOIL  FLUENT
  - Cl Distribution: Constant
  - r/R : Spinner [ ] Tip [ ]
  - Cl : Const [ ] 0.60 [ ] Const [ ]
- Air Property:**
  - Altitude: 0 km [Compute]
  - Density (kg/m<sup>3</sup>): 1.2250
  - Temperature (K): 288.16
  - Kinematic Viscosity (m<sup>2</sup>/s): 1.4604e-06
  - Speed of Sound (m/s): 340.30
- Prop\_Test List:** Prop\_Test, Prop\_Test2, Prop\_Test3
- Buttons:** Design, Reset, Store, Delete, OK, Cancel



# 설계 Tool 개발 (2)

## Off-Design Analysis Window

Off-Design Analysis

Propeller List

- Prop\_Test
- Prop\_Test2
- Prop\_Test3

Tip Loss Correction

- No Tip Correction
- Prandtl's Tip Loss
- Wilson and Lissaman
- de Vries
- Shen

Velocity (m/s)

RPM

Analysis

Section Results Plot

J	CT	CP	Eta
0.4800	0.0412	0.0246	0.8039
0.5200	0.0365	0.0230	0.8252
0.5600	0.0315	0.0211	0.8360
0.6000	0.0261	0.0186	0.8419
0.6400	0.0192	0.0148	0.8303
0.6800	0.0113	0.0099	0.7762
0.7200	0.0035	0.0047	0.5362

Up Down Delete Clear

Export to File Close

Air Property

Altitude

Density (kg/m<sup>3</sup>)

Temperature (K)

Kinematic Viscosity (m<sup>2</sup>/s)

Speed of Sound (m/s)

J

Thrust (N)

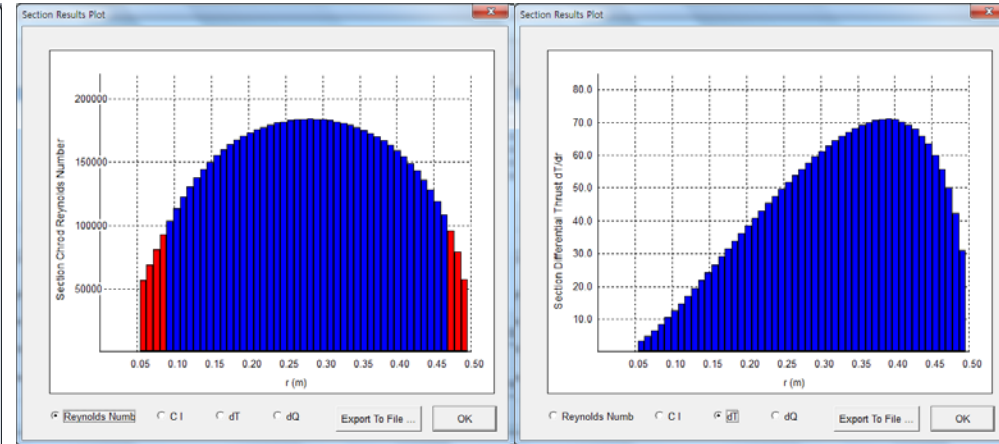
Torque (Nm)

Power (W)

Thrust Coefficient

Power Coefficient

Propeller Efficiency



## Performance Curve Window

Performance Curve

Advance Ratio Range  ~

Number of Intervals

- Fixed Velocity
- Fixed RPM
- Overwrite Curve

Plot Clear Options...

Air Property

Altitude

Density (kg/m<sup>3</sup>)

Temperature (K)

Kinematic Viscosity (m<sup>2</sup>/s)

Speed of Sound (m/s)

Tip Loss Correction

- No Tip Correction
- Prandtl's Tip Loss
- Wilson and Lissaman
- de Vries
- Shen

Export to File Close

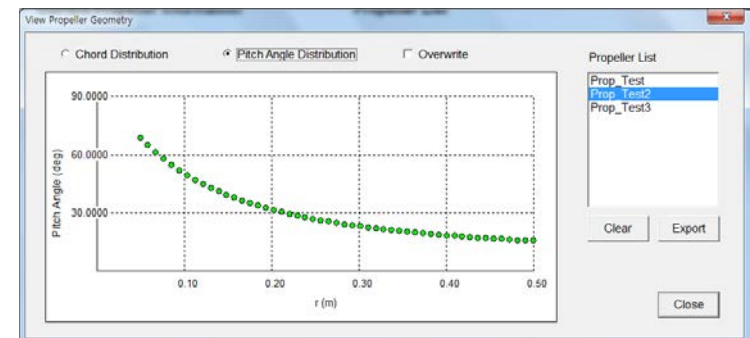
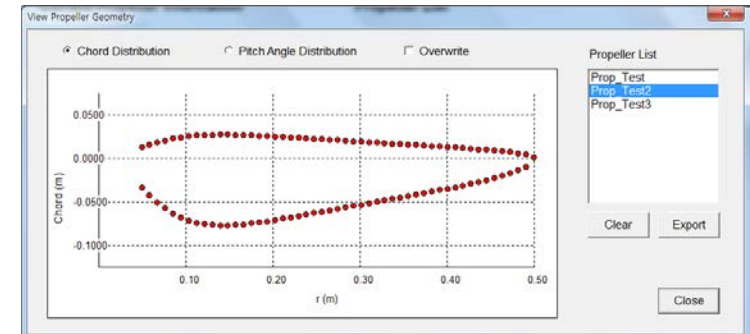
Propeller List

- Prop\_Test
- Prop\_Test2
- Prop\_Test3

Curve List

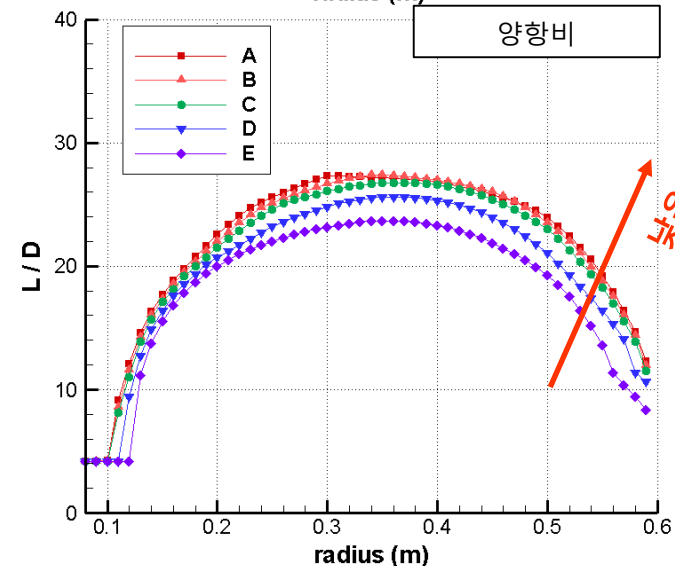
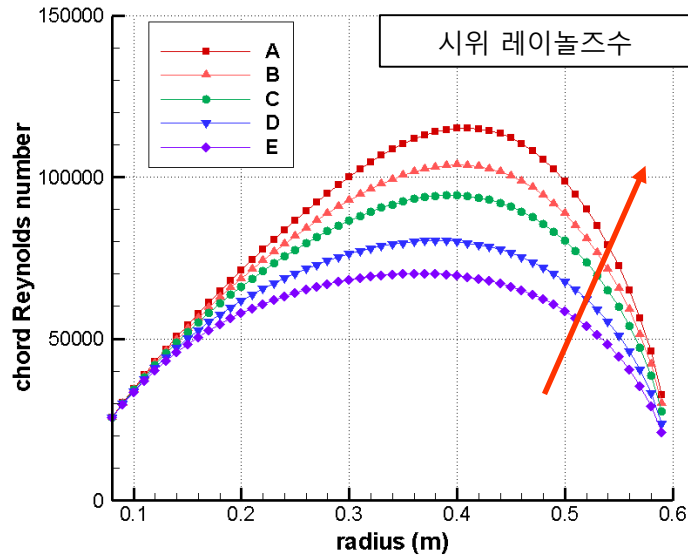
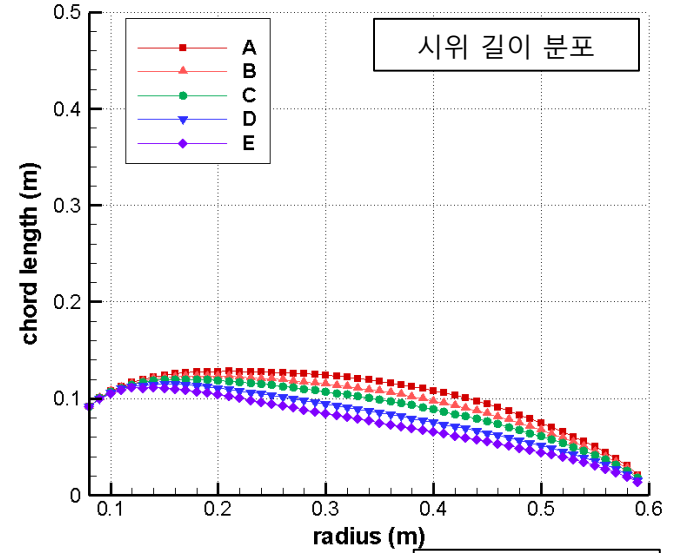
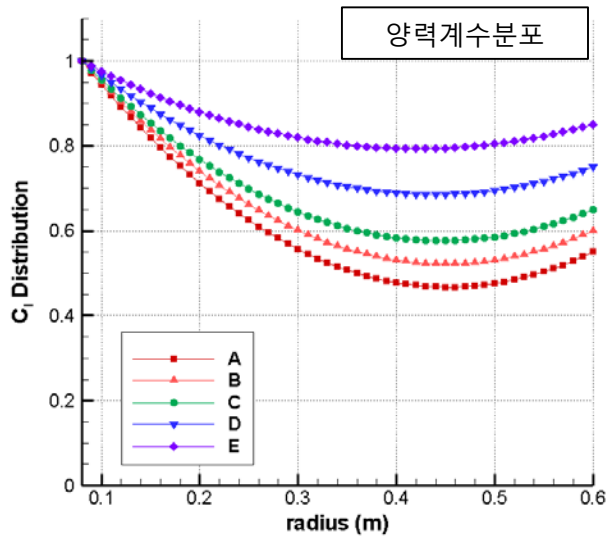
Name	Propeller	JMin	JMax	Intervals
Curve1	Prop_Test	0.35	0.7	20
Curve2	Prop_Test2	0.45	0.8	20

Store Delete Delete All



# 주요 설계 변수 식별

❖ 식별 설계 변수 - 직경, 설계점 회전수, 양력계수 분포



낮은 양력계수 분포

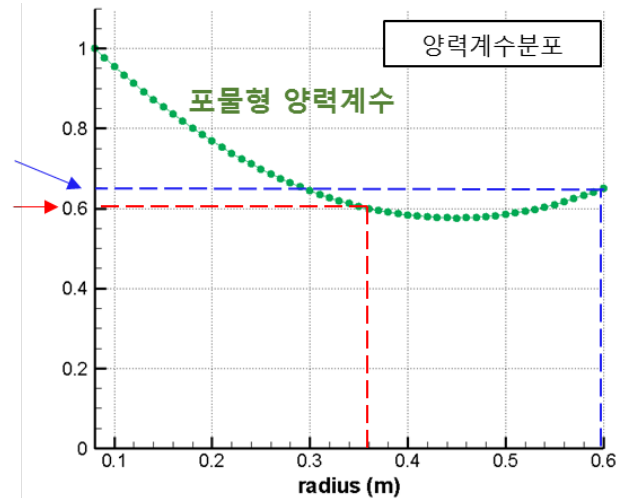
# 근사모델 기반 최적 설계 (1)

## ❖ 설계변수 정의

Var. 1	<b>rpm</b>	설계점 회전속도
Var. 2	<b>d</b>	프로펠러 직경
Var. 3	<b>clm</b>	반경 60% 지점 양력계수
Var. 4	<b>clt</b>	끝단 양력계수

(포물형 양력계수 분포를 가정)

clt=0.65  
clm=0.6



## ❖ Response 정의

<b>Eff</b>	설계점 (고도 15km 상승조건) 효율
<b>Q_Sea</b>	지상 상승조건 만족 시 요구토크
<b>RPM_18</b>	고도 18km 상승조건 만족 시 필요 rpm

# 근사모델 기반 최적 설계 (2)

## ❖ 목적함수

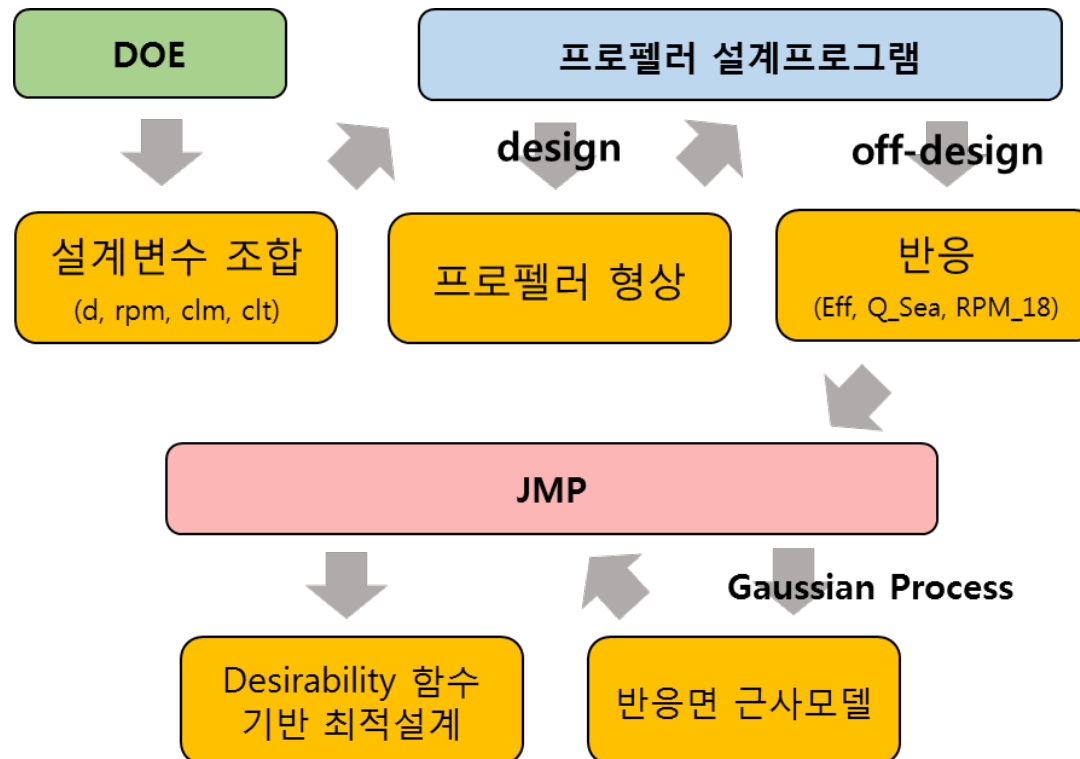
Maximize Eff

## ❖ 제약조건

$Q_{Sea} \leq 3.82 \text{ Nm}$

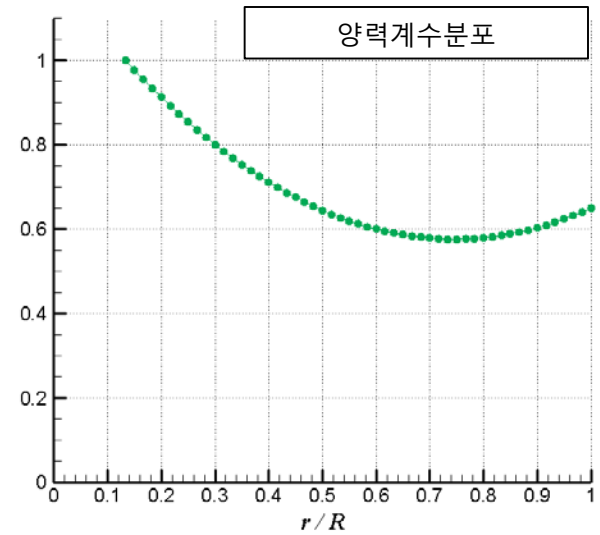
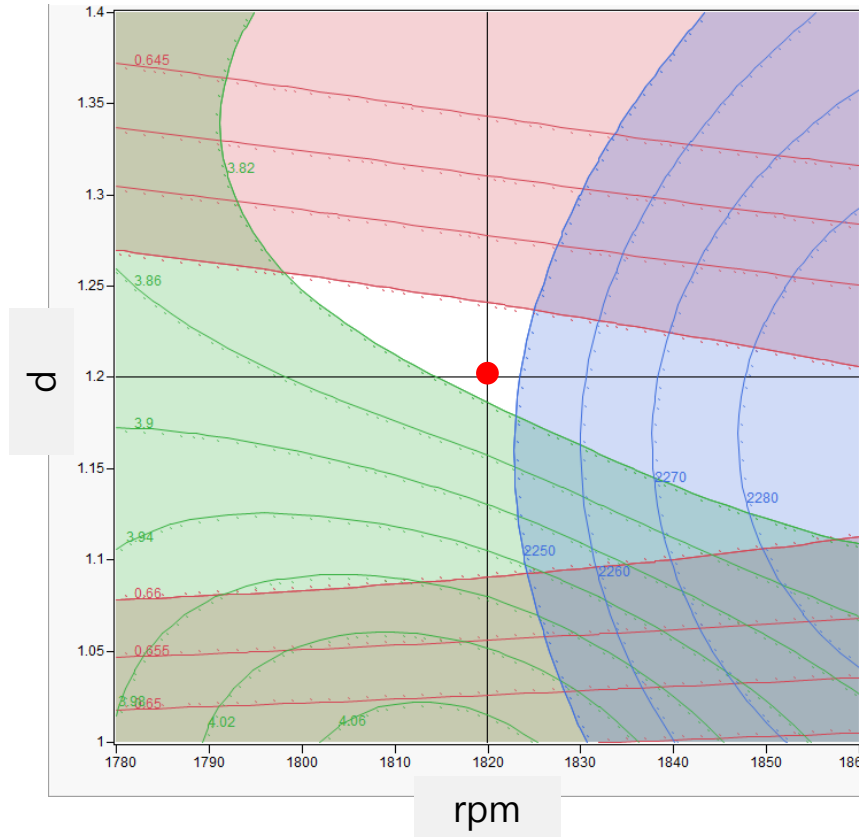
$RPM_{18} \leq 2250$

## ❖ 근사 모델 기반 최적 설계 절차



# 근사모델 기반 최적 설계 (3)

## ❖ 반응면 평가 - Example



- Eff 66% 이하
- Q\_Sea 3.82 이상
- RPM\_18 2250 이상
- 설계 가능 영역
- 설계 프로펠러

DOE

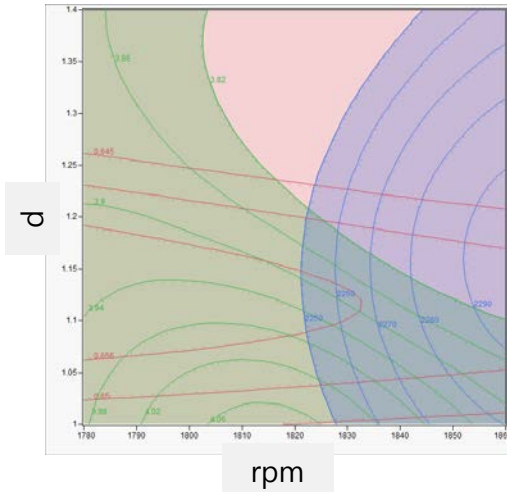
: Response Surface, CCD

: Space Filling, Latin Hypercube

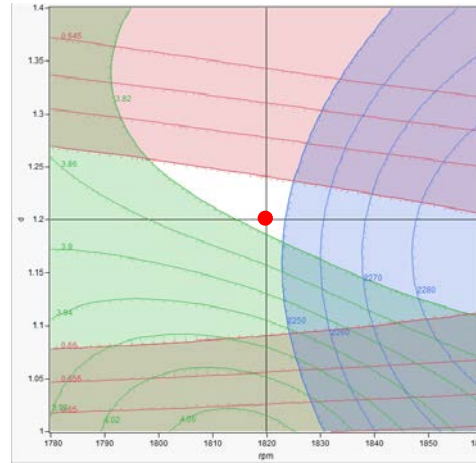


# 근사모델 기반 최적 설계 (4)

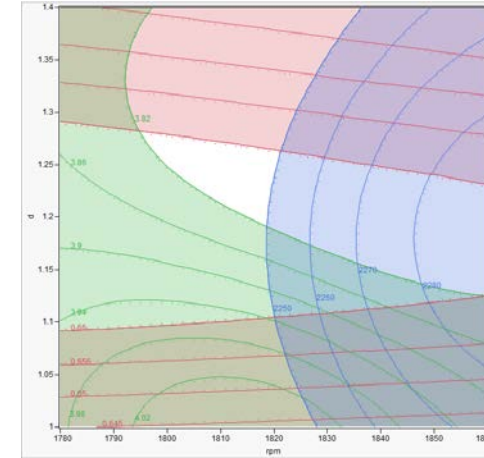
- $clm=0.65$  &  $clt=0.70$



- $clm=0.60$  &  $clt=0.65$

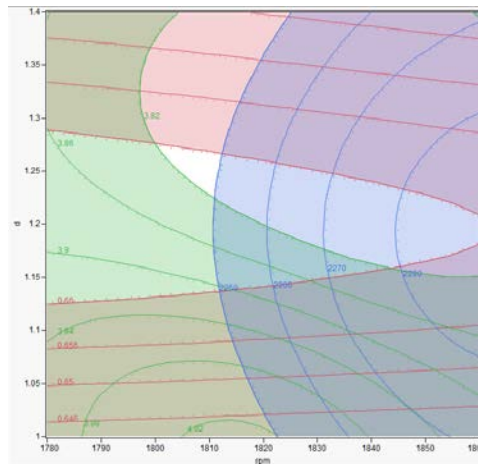


- $clm=0.55$  &  $clt=0.60$

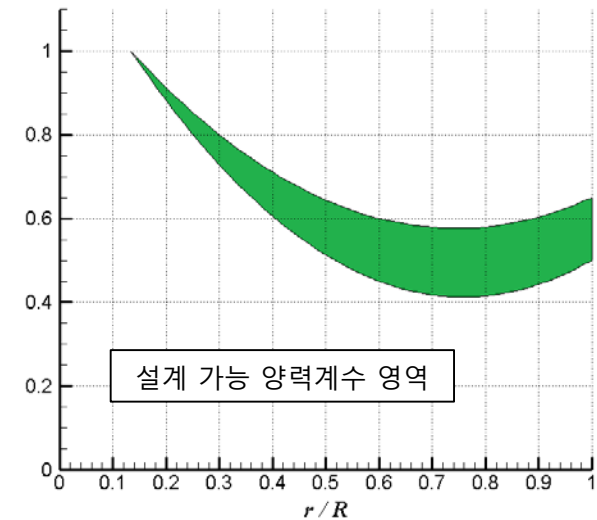
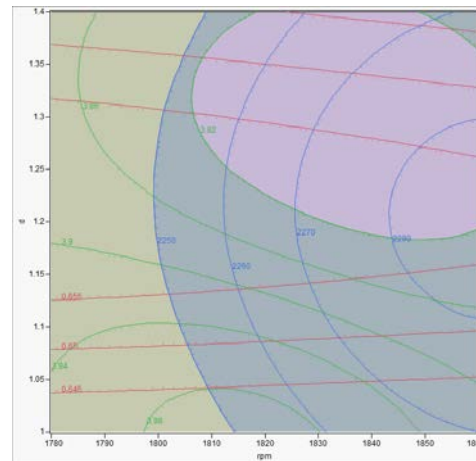


- 제한된 양력계수 범위에서만 설계 가능 영역이 존재

- $clm=0.50$  &  $clt=0.55$



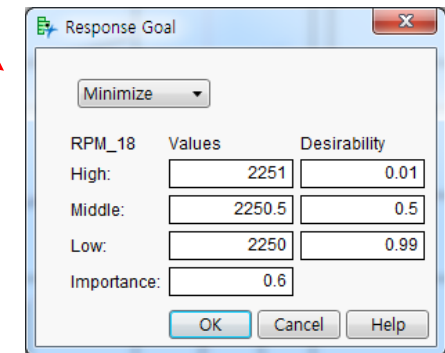
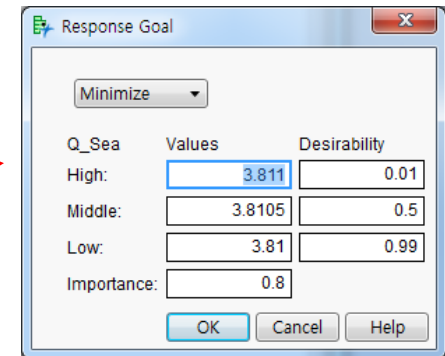
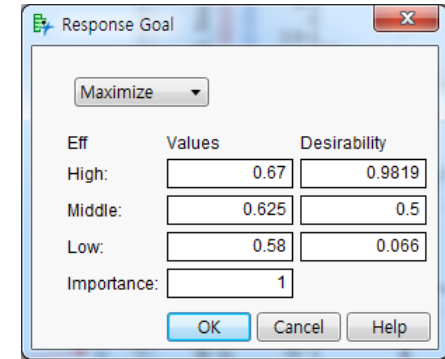
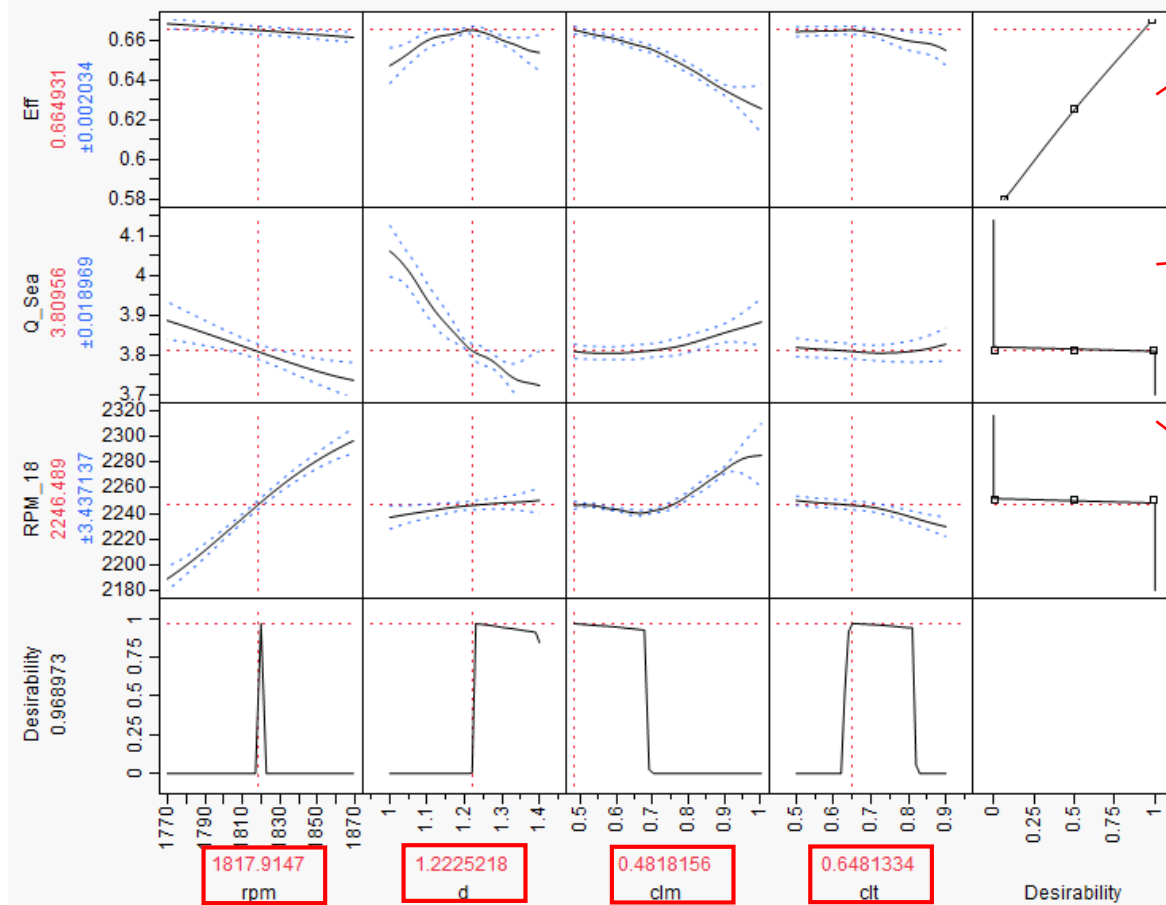
- $clm=0.45$  &  $clt=0.50$



# 근사모델 기반 최적 설계 (5)

## ❖ 선호도 함수 기반 최적 설계

Desirability	방향	제약조건	중요도
Eff	최대화	-	1.0
Q_Sea	최소화	3.81 이하	0.8
RPM_18	최소화	2250 이하	0.6

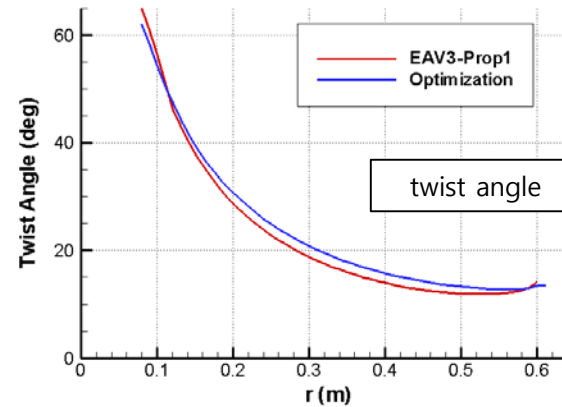
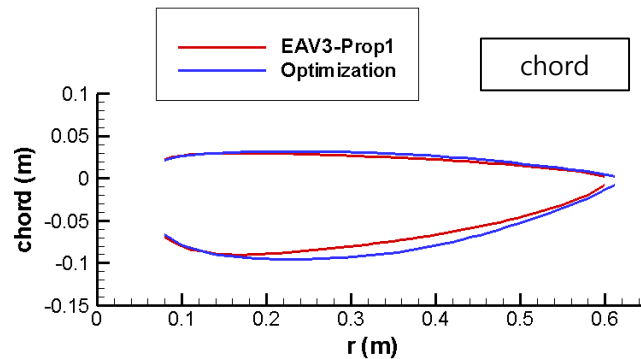


# 근사모델 기반 최적 설계 (6)

## ❖ 설계 변수 비교

	rpm	d	clm	clt
설계	1820	1.2	0.6	0.65
Optimization	1817.91	1.223	0.4818	0.6481

## ❖ 형상 비교



## ❖ 예상 성능 비교

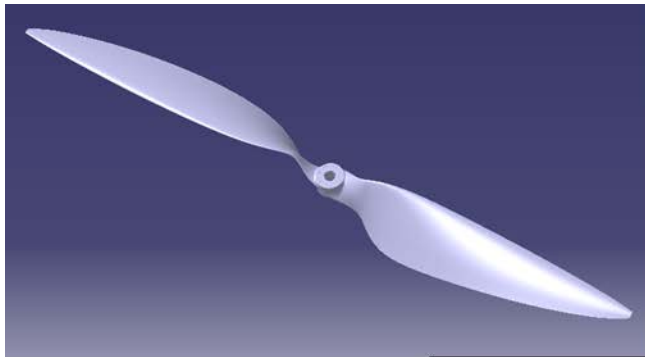
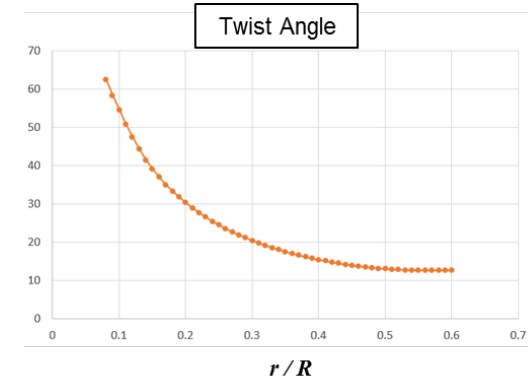
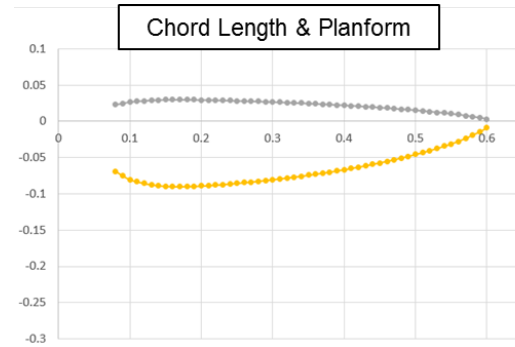
	지상고도 상승조건		고도 15km 상승조건	고도 18km 상승조건	
	토크	효율	효율	RPM	효율
기존설계	3.819	64.86%	66.04%	2246.67	64.61%
Optimization I	3.809	65.45%	66.33%	2247.18	64.86%



# 설계 프로펠러

## ❖ EAV-3 프로펠러

Airfoil	DAE51
프로펠러 직경	1.2 m
Spinner 직경	0.16 m
양력계수 분포	0.576 ~ 1.0 / Parabolic
설계 기준	고도 15km 조건 with 1820 RPM



3D Modelling

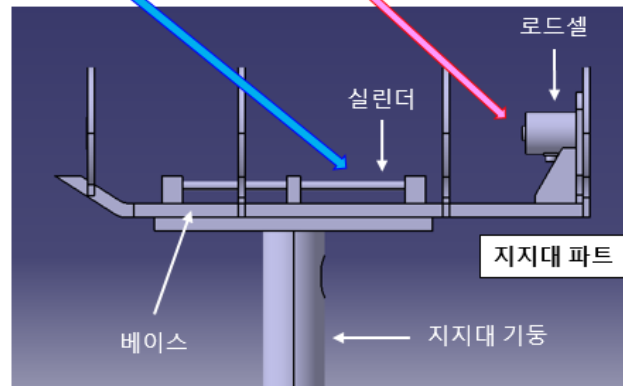
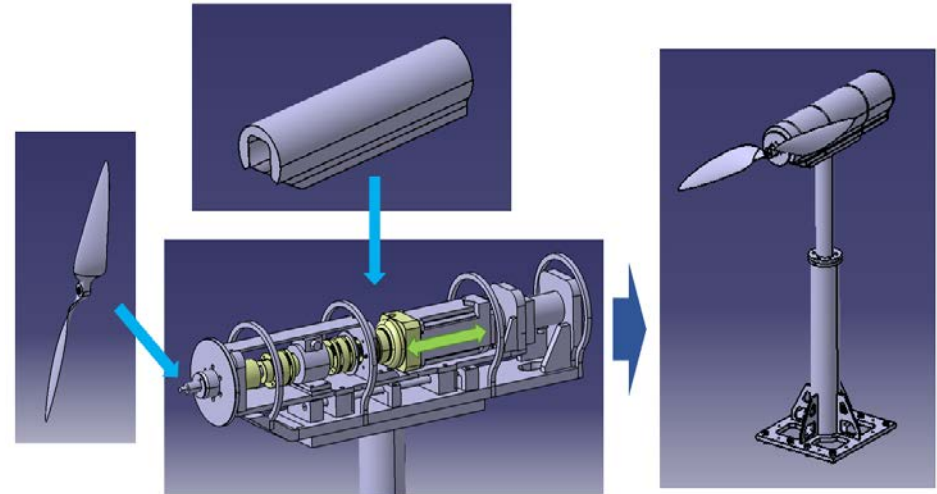
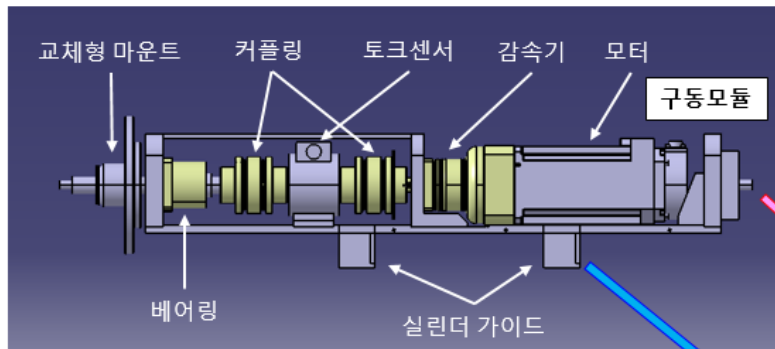


Manufacture (CFRP)

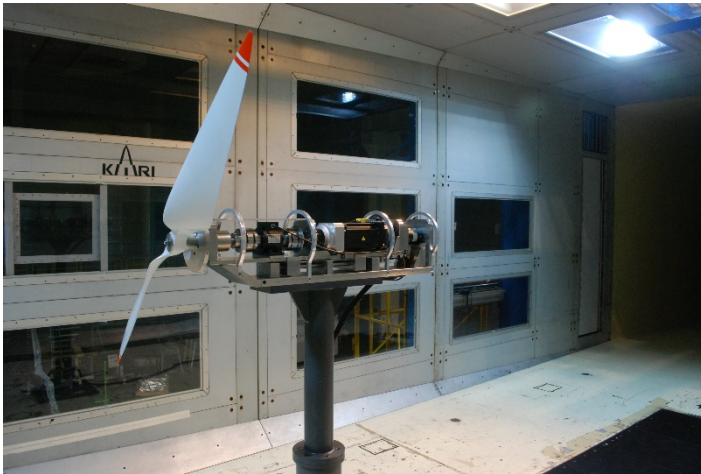
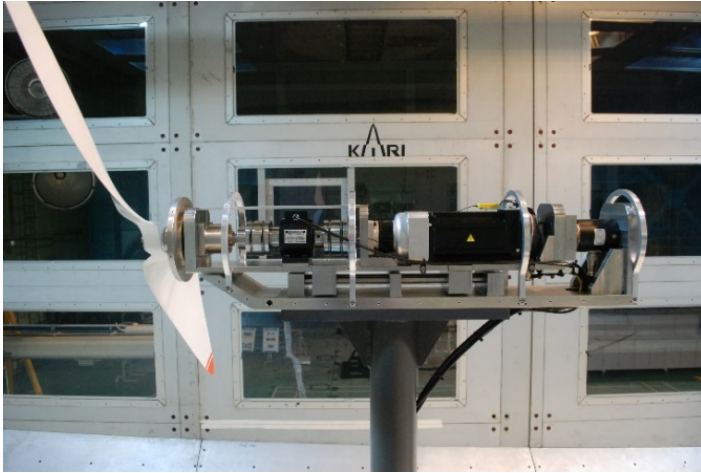
# 풍동시험 (1)

## ❖ 시험장치 설계

- RPM 정밀제어, 추력/토크 동시 측정 장치 설계/제작



# 풍동시험 (2)

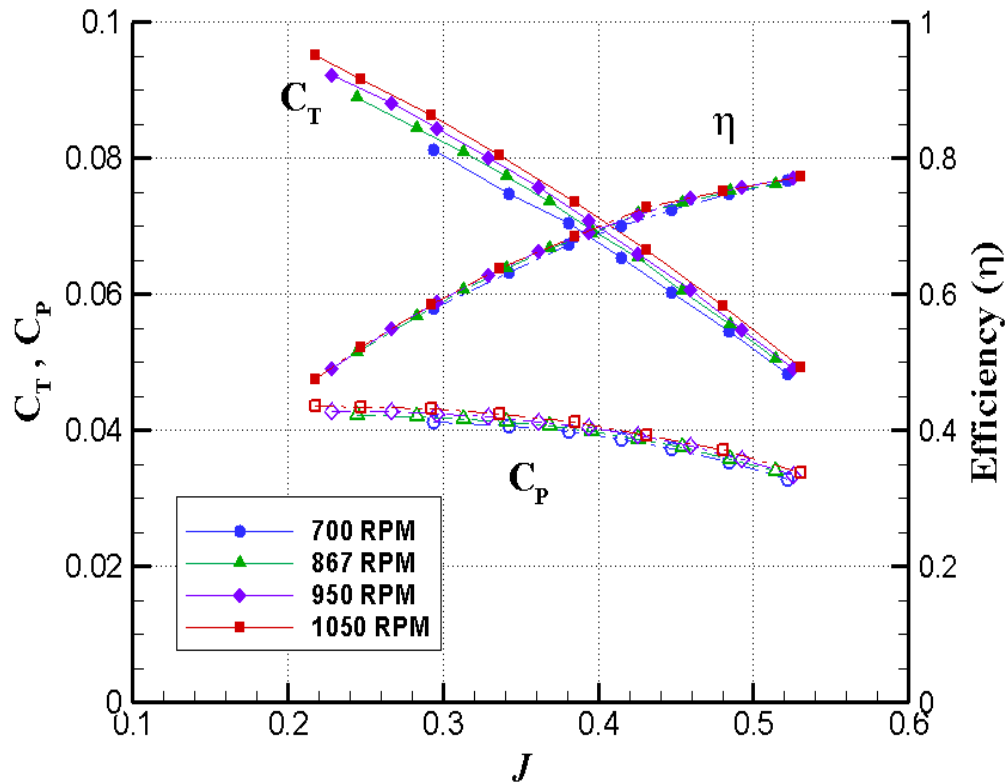


- 센서 교보정 시험
- 센서 교정인자 및 보정인자 도출
- Glauert blockage correction 적용
- 시험부 동압 영점 보정 적용

# 풍동시험 (3)

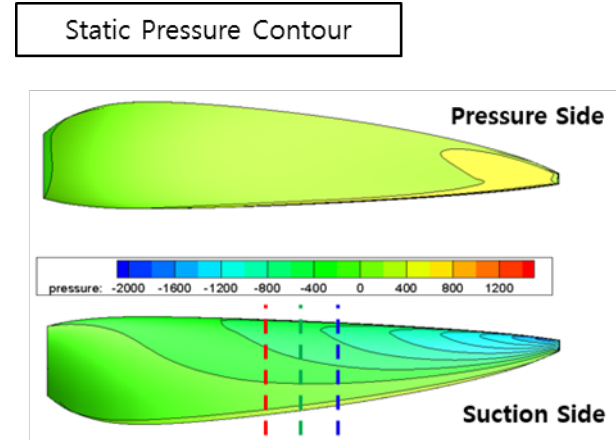
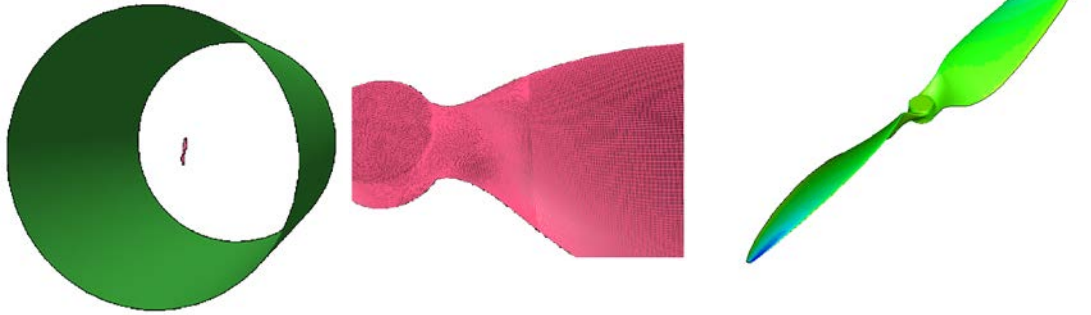
- 성능 계수 곡선 획득
- RPM에 따라 레이놀즈수 영향 발생 확인
- 저속 조건에서 자유류 상태 불확실성 증가

전진비	추력계수	동력계수	효율
$J = \frac{V}{nD}$	$C_T = \frac{T}{\rho n^2 D^4}$	$C_P = \frac{Q\omega}{\rho n^3 D^5}$	$\eta = \frac{TV}{Q\omega} = J \frac{C_T}{C_P}$

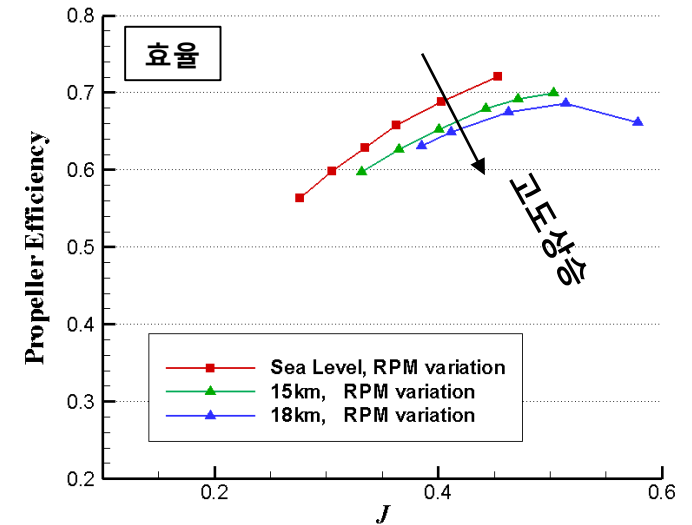
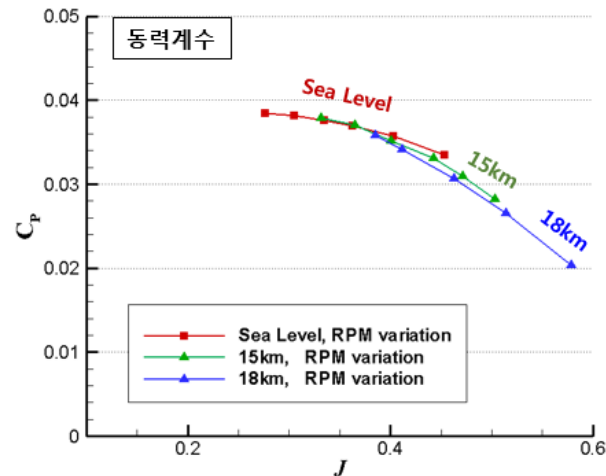
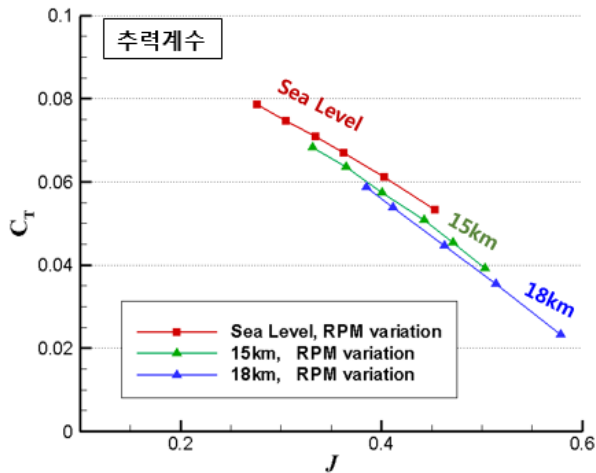


# 전산해석 (1)

## ❖ 기본성능해석



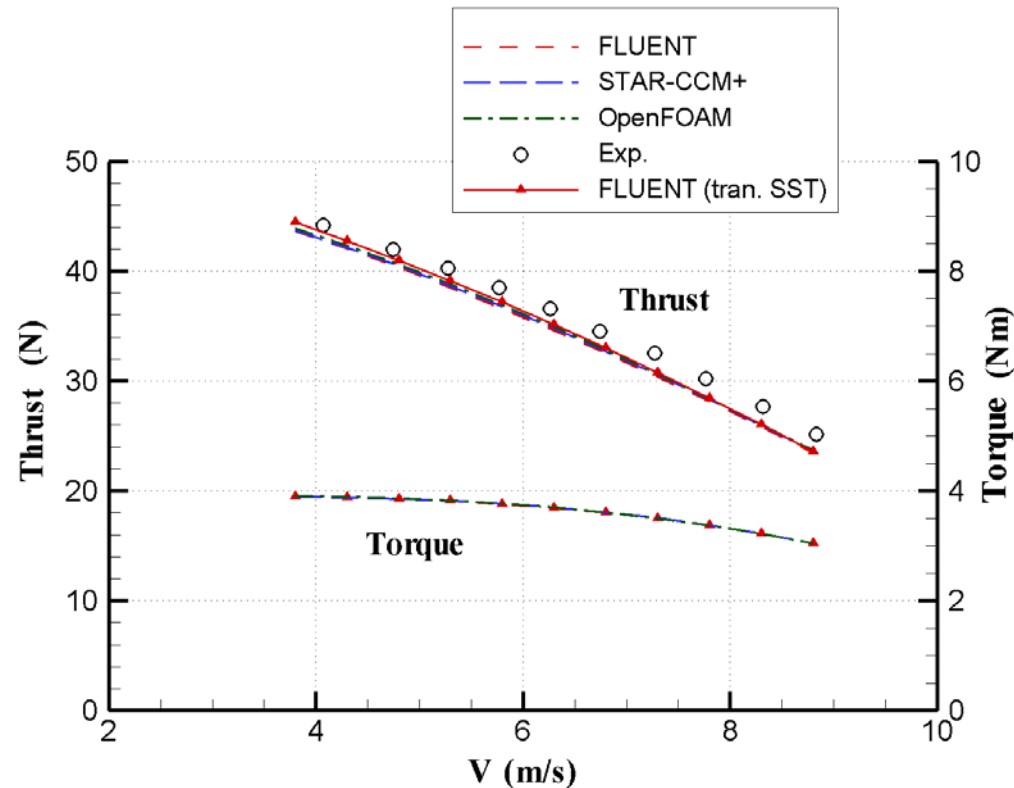
- 고도별 성능 변화 예측: 고도 증가에 따라 효율 곡선의 저하



# 전산해석 (2)

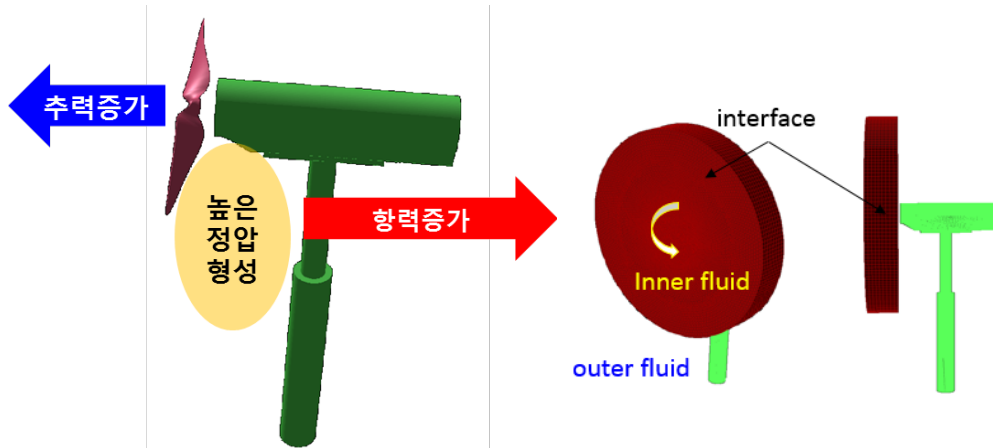
## ❖ 단독성능해석

- 2종의 상용코드, 1종의 오픈소스 코드 / 난류모델 (2eqns & 4eqns)
- 풍동 시험 측정 추력이 동일 속도 기준으로 CFD 대비 소폭 높게 나타남

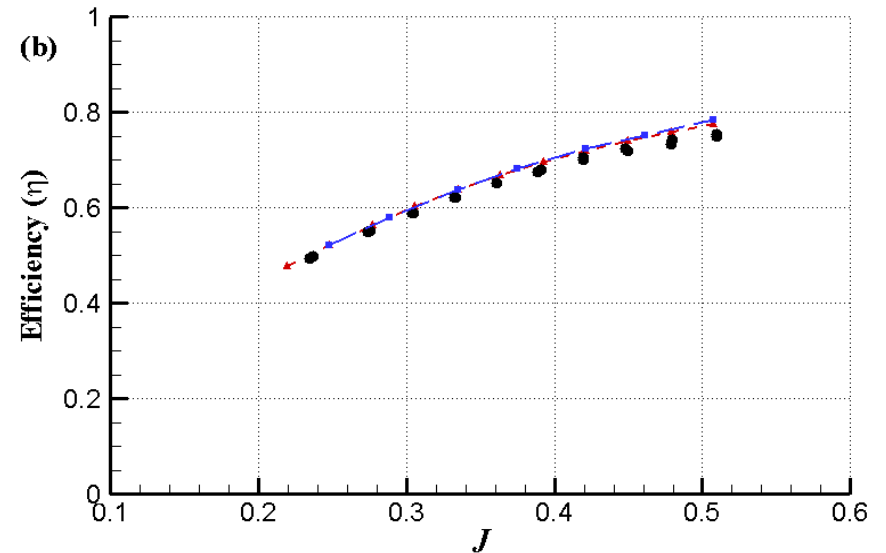
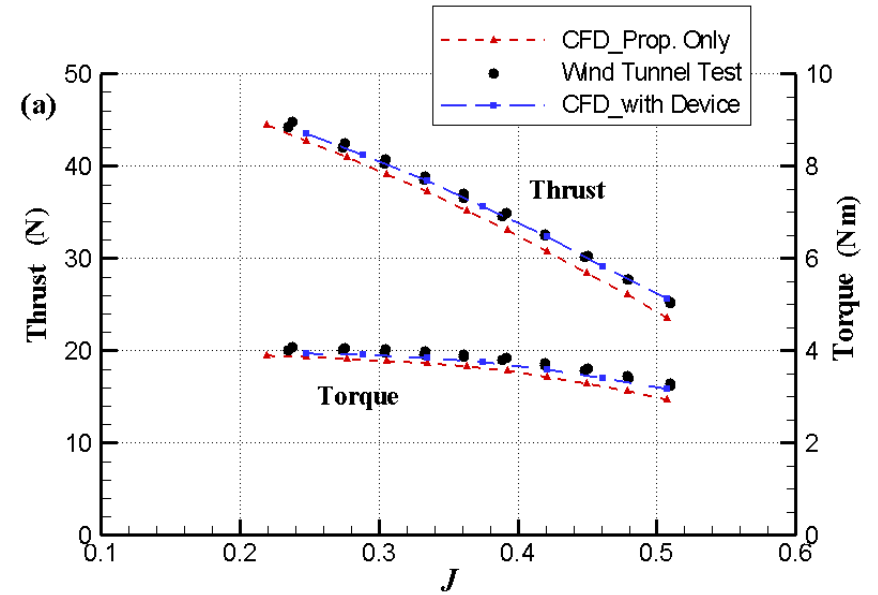
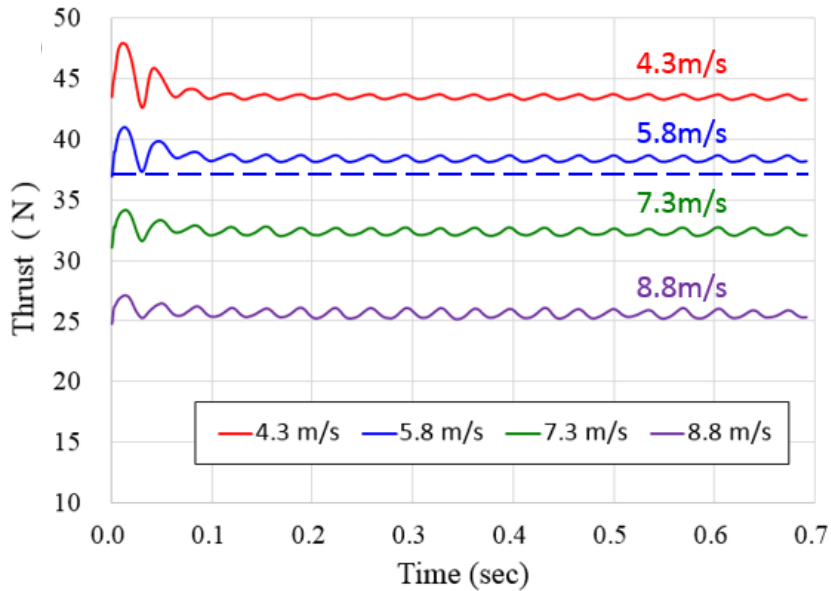


# 전산해석 (3)

## ❖ 시험장치 폐쇄효과

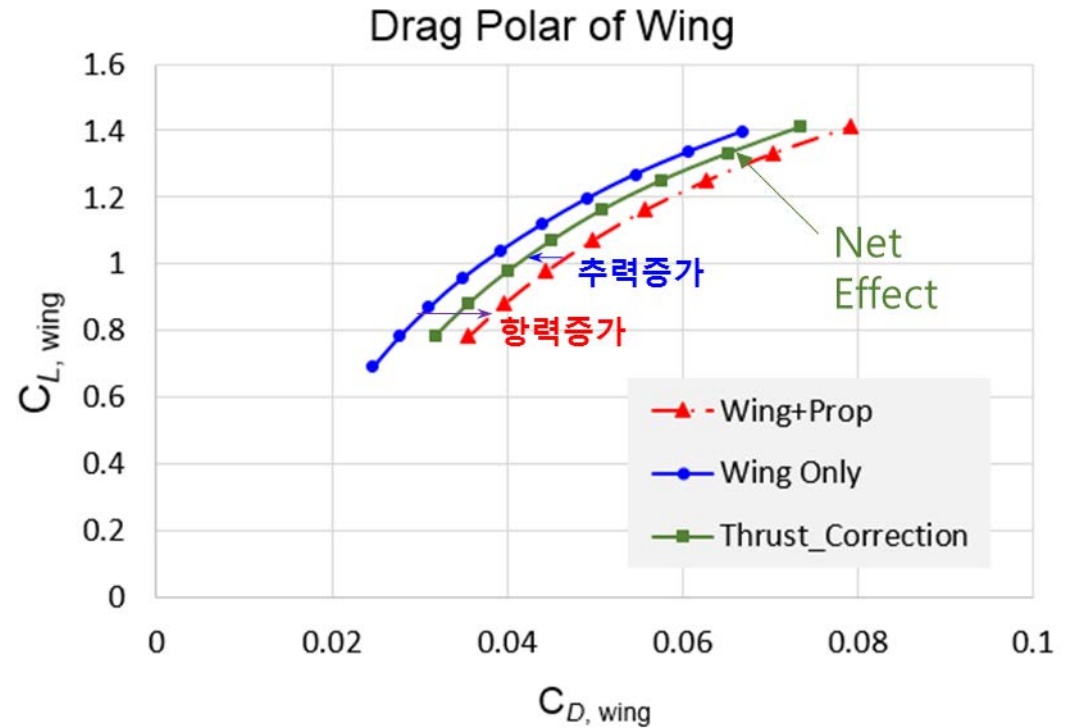
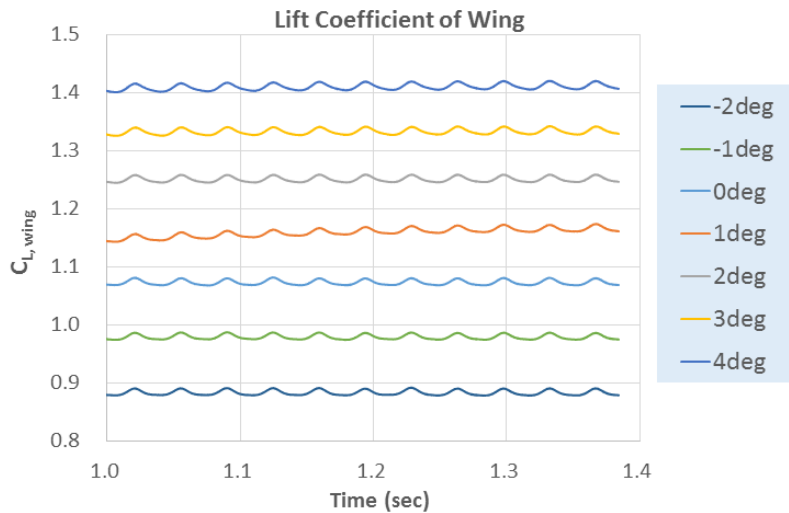
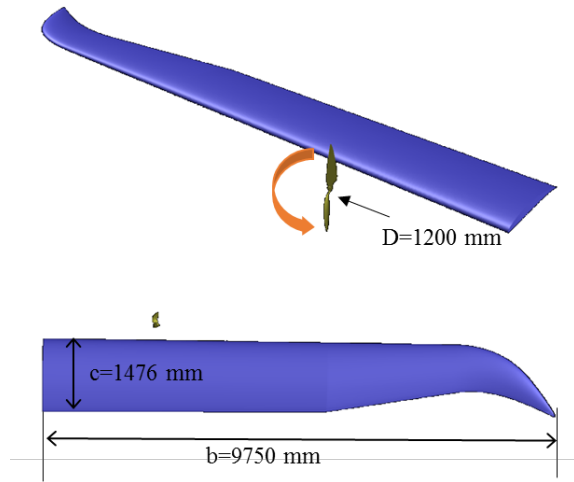


- 시험장치 폐쇄효과로 인해 추력 소폭 증가



# 전산해석 (4)

## ❖ Power-on Effect

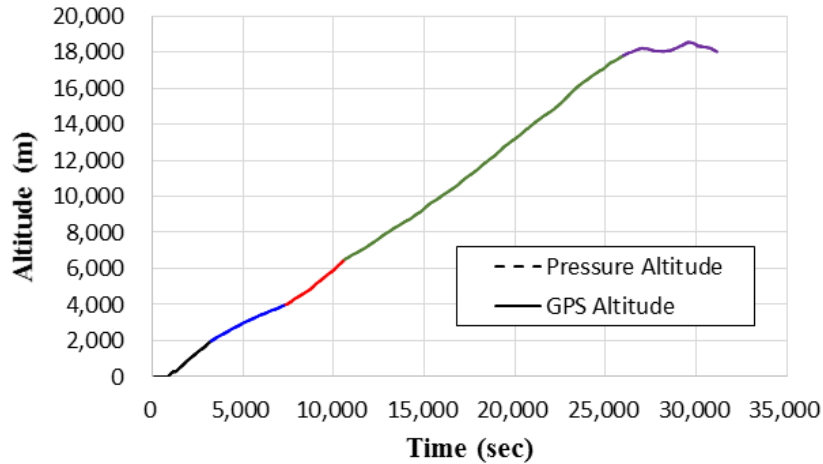


- 동일 양력계수 기준, 조건에 따라 최대 50 counts 수준의 항력 증가 유발 가능

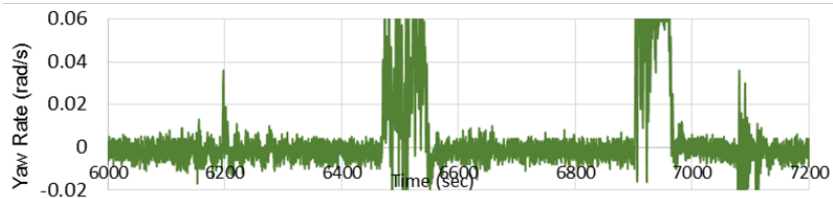
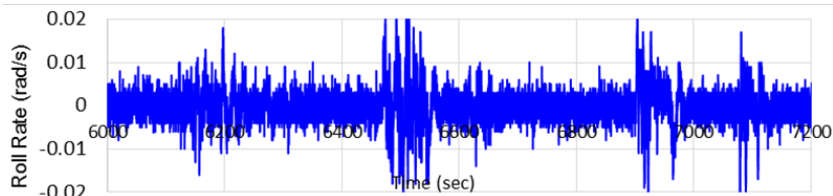
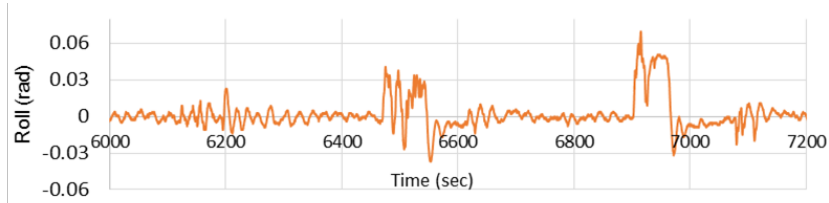
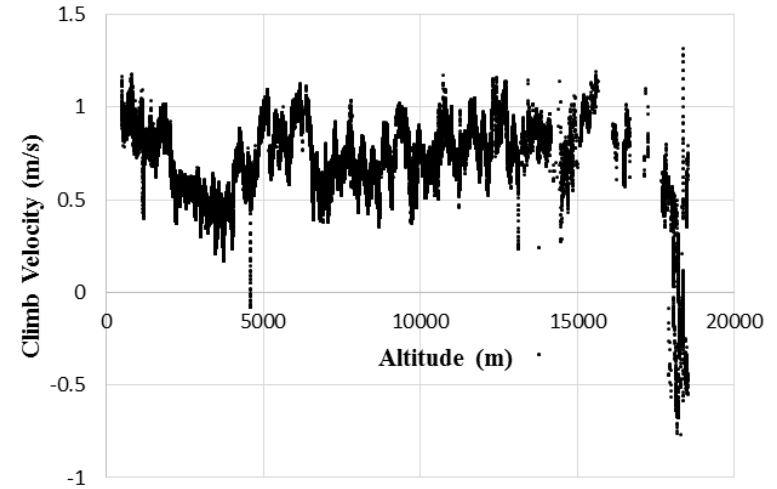


# 비행시험 분석 (1)

## ❖ 비행시험 데이터 특성



- 상승속도 이력



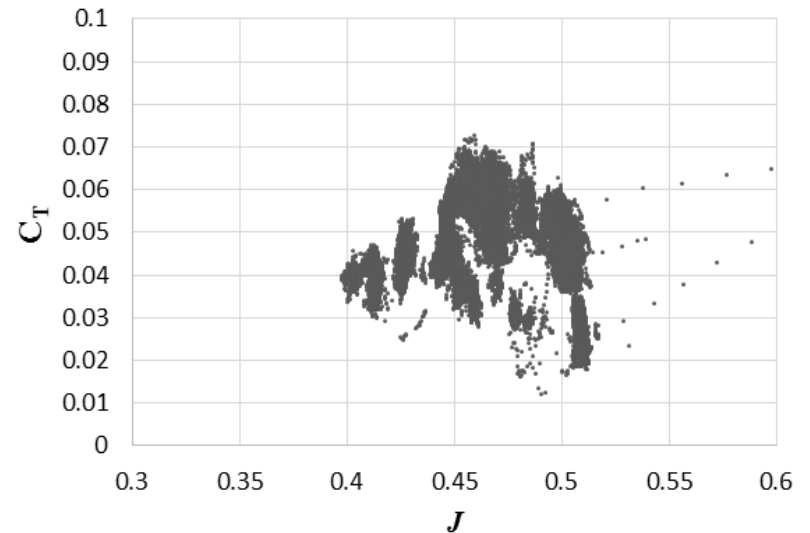
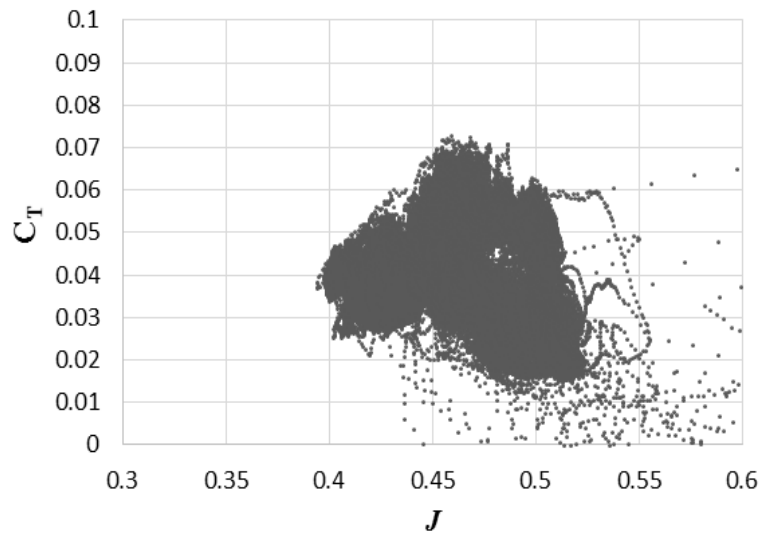
# 비행시험 분석 (2)

## ❖ 데이터 필터링

- 정상상태의 단순상승 비행에 가까운 조건들만을 선정하기 위해 자세각 및 조종각 범위 제한

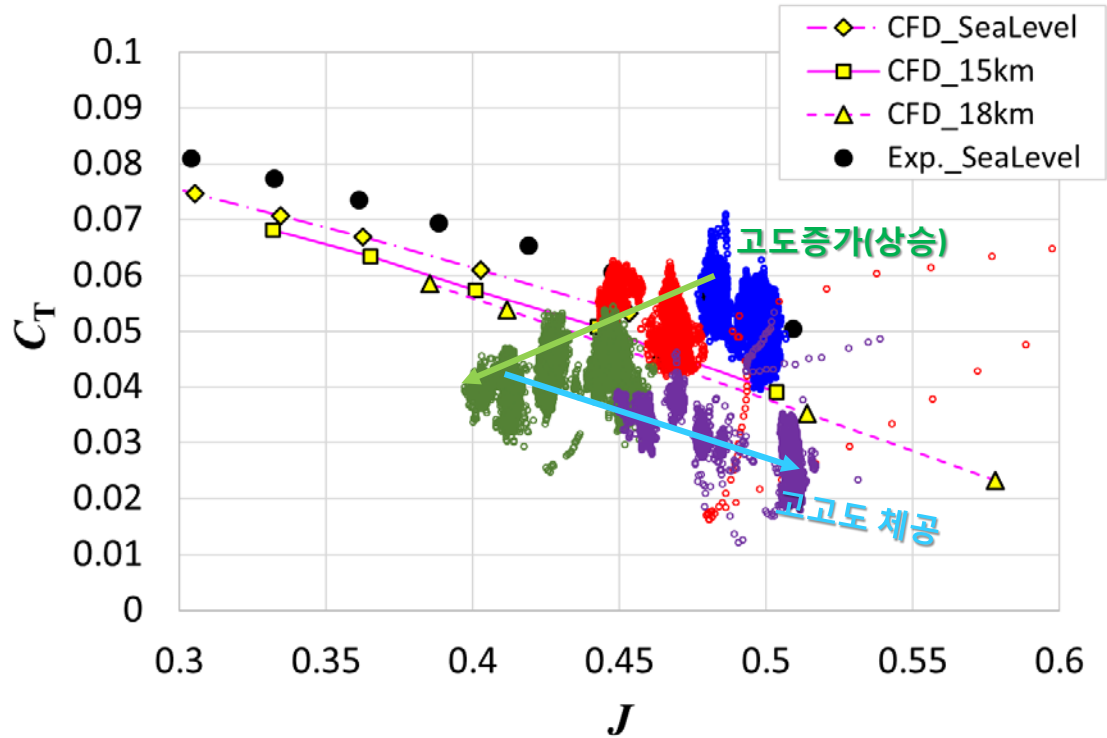
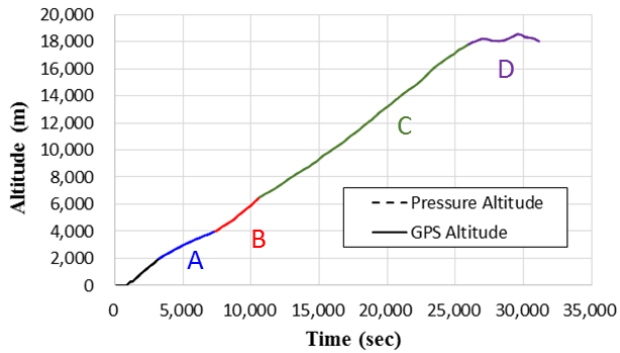
Roll	Roll Rate	Yaw Rate	Aileron (<17km)	Rudder (<17km)
-0.015 ~ 0.015	-0.006 ~ 0.006	-0.01 ~ 0.01	-2 ~ 2	-3 ~ 3

### Example) 예측 추력계수



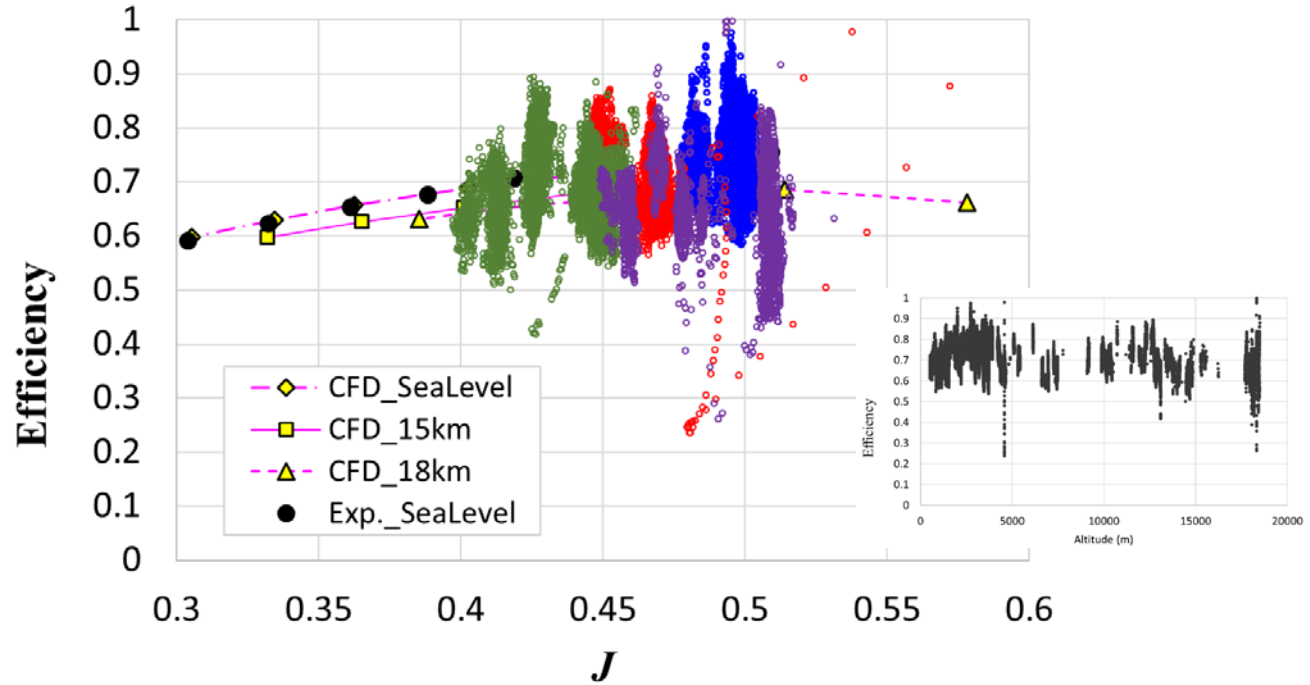
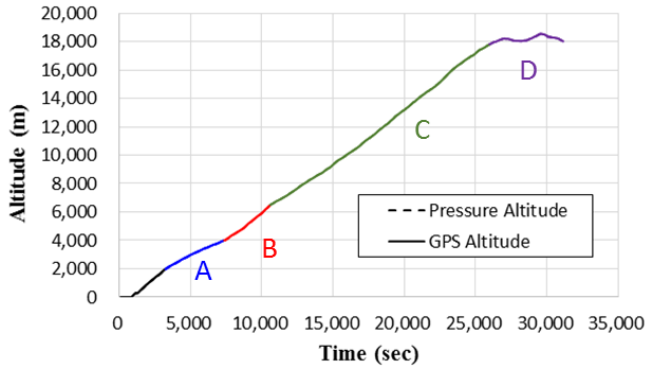
# 비행시험 분석 (3)

## ❖ 추력계수



# 비행시험 분석 (4)

## ❖ 효율



# Concluding Remarks

## ❖ HALE UAV: EAV-3 프로펠러 개발

- 고고도 운용 조건 고려 - 저레이놀즈수 공력 특성 설계 반영
- 모터 제약 조건 고려 - 근사모델 기반 최적 설계를 활용
- 기본 프로펠러 설계 프로그램 개발
- 프로펠러 설계 / 풍동시험 / 전산해석 / 비행시험 분석 수행
- 고고도 운용 프로펠러 설계 기술 확보 및 타당성 평가



감사합니다.



[parkdh@pusan.ac.kr](mailto:parkdh@pusan.ac.kr)



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