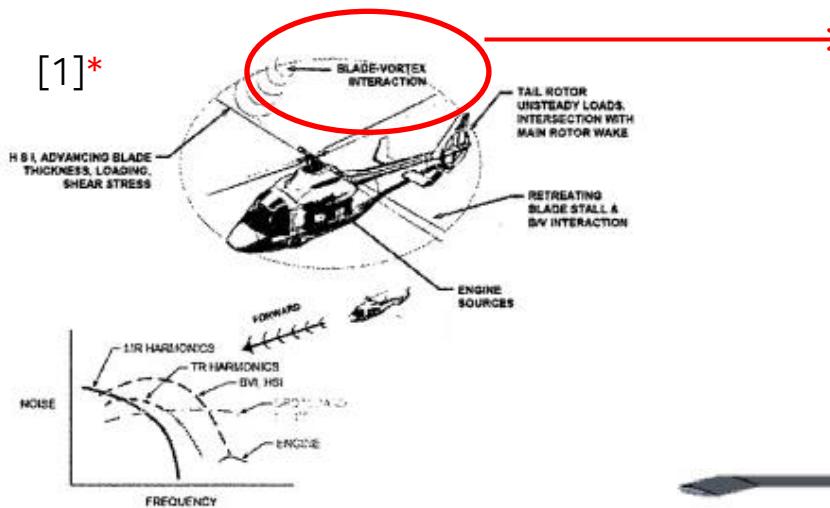


1. 프로젝트 목적



BVI(Blade Vortex Interaction) 소음은
헬리콥터 소음의 주요한 원인

이를 줄이기 위해
최적의 로터 형상을 찾는 연구들이 진행됨



Anhedral tip이 그 대안으로 제시됨

그림 3 헬리콥터 소음원 및 전형적인 스펙트럼 [Ref. Edwards et al.]

1. 프로젝트 목적

[1]*

ABSTRACT

In 2015, Airbus Helicopters unveiled the secrecy around its Dauphin successor and presented the all new H160 helicopter. A special feature immediately attracting attention is its unusual and revolutionary fore-aft swept main rotor blade. This design, aiming at reducing the blade-vortex interaction noise signature and also reducing fast forward flight power requirements, finds its origins far back in the 90s, when DLR and ONERA formed a joint team to acoustically optimize a rectangular reference rotor blade. Based on state-of-the-art comprehensive rotor codes and a 50-50 work share, the ERATO rotor blade design was developed, patented worldwide and tested on a rotor test rig and in the wind tunnel. Airbus Helicopters took up that design, optimized hover and forward flight high lift performance and prepared it for serial production, until it finally made it as the Blue Edge™ rotor blade on the H160 helicopter. The paper covers the history and technical achievements, wind tunnel test results and flight tests.



Figure 10. The ONERA-DLR ERATO rotor mounted in the SIMA 8 m Ø closed test section.



Figure 33: Molded structure of the experimental Blue Edge™ blade.

BVI 소음을 줄일 수 있는 이점

- Airbus, ONERA(프랑스 국립항공우주연구소) 연구팀이 2015년 최초로 상용 Anhedral tip blade 개발, H160 헬리콥터에 장착

- Tip 외에도 다양한 공기역학적 설계들이 포함

Tip 자체의 영향만을 고려할 수는 없을까?

[1] Wall, Berend & Beaumier, Philippe & Pengel, K. & Kessler, Christoph & Head, Rotorcraft & Hirsch, Jean-François & Crozier, Pascal & Hirsch, Jeff. (2019). From ERATO Basic Research to the Blue Edge TM Rotor Blade.

1. 프로젝트 목적

Aerodynamic Performance and Aeroacoustic Characteristics of

[1]* Model Rotor with Anhedral Blade Tip in Hover

Huang Shuilin, Fan Feng*, Yuan Mingchuan, Sun Wei

National Key Laboratory of Science and Technology on Craft Aeromechanics Laboratory, China Helicopter Research and Development Institute, Jingdezhen 333001, P. R. China

(Received 23 June 2016; revised 2 August 2016; accepted 16 August 2016)

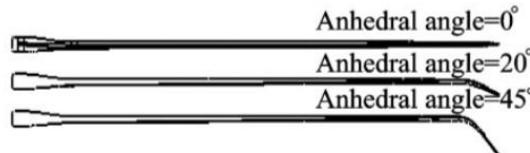


Fig. 1 Schematic of the blade tip with different anhedral angles

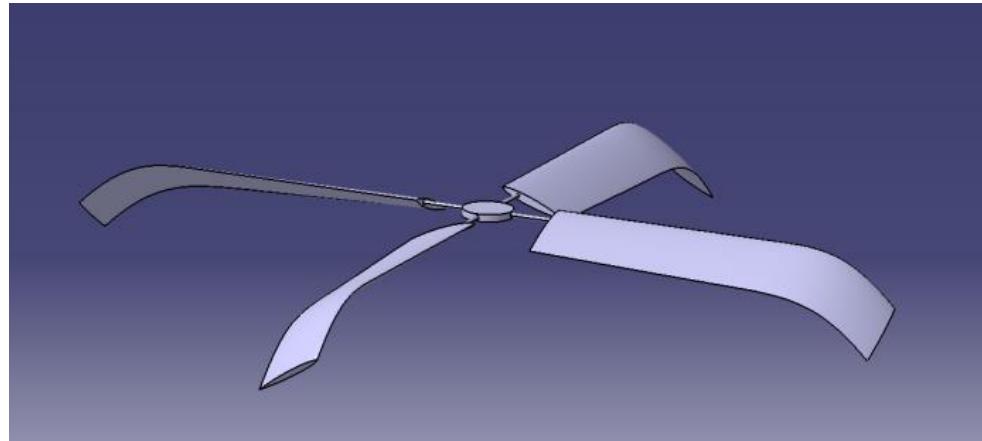


Fig. 2 Test environment and experiment stand

→ 단순한 blade 형상 사용,
anhedral angle만 바꾸어서 공력, 소음성능 분석

→ 실제 blade의 airfoil 형상과 다른
받음각 등의 각도 고려 X
but

1. 프로젝트 목적



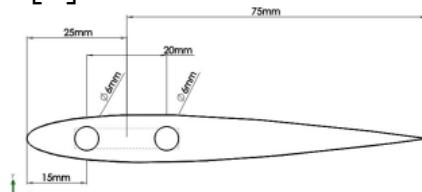
본 프로젝트에서 사용한 blade (tip angle = 45도)

프로젝트의 목표

- 1) 기존의 연구보다 더 발전된 형상(유선형 airfoil, 반음각 설정)을 설계, anhedral tip에 따른
공력, 소음 성능 분석
- 2) 여러 선행 연구 결과와 비교, 결과의 신뢰성 확보

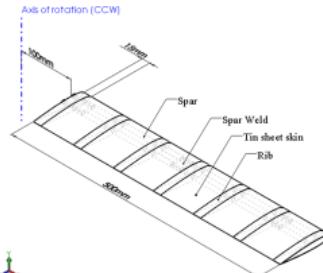
2. 프로젝트 과정

[1]*

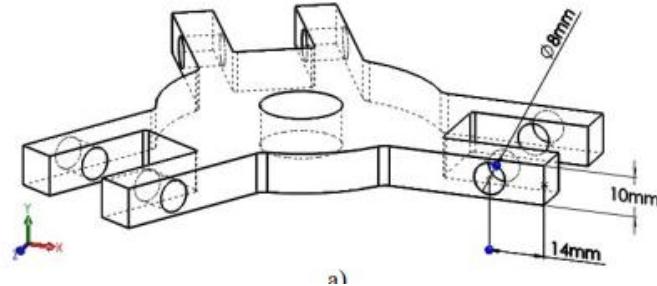


a)

Fig. 6. a) Front view of blade, b) 3D view of blade

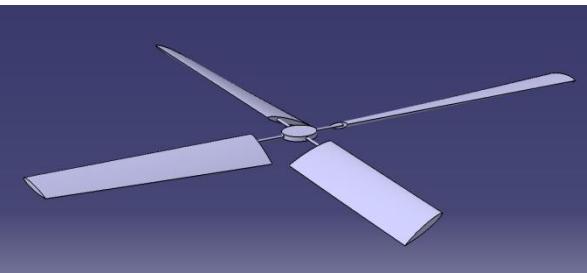


b)

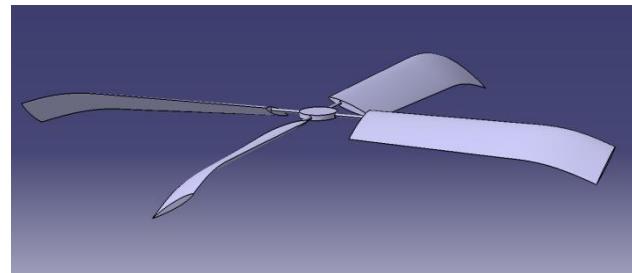


a)

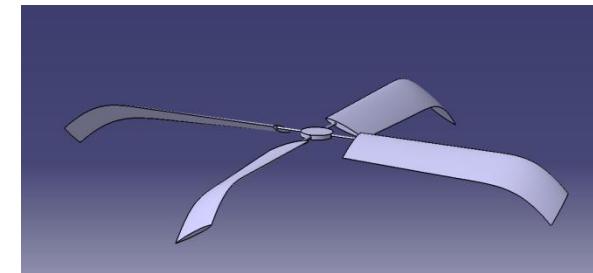
NACA 0012 Airfoil 사용, 기존에 설계된 blade 도면을 참고, 총 3개의 model를 새롭게 제작함



Tip angle = 0deg



Tip angle = 20deg

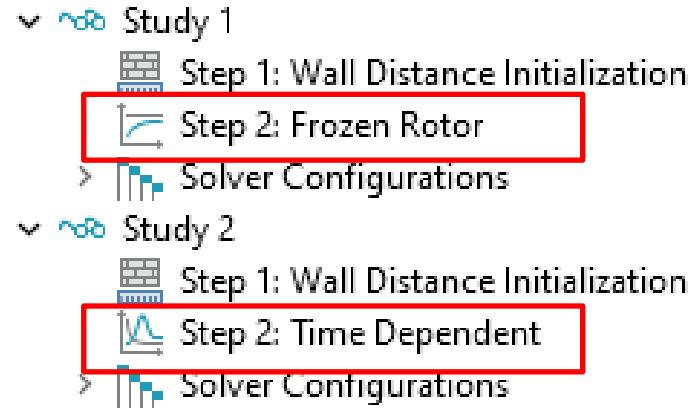
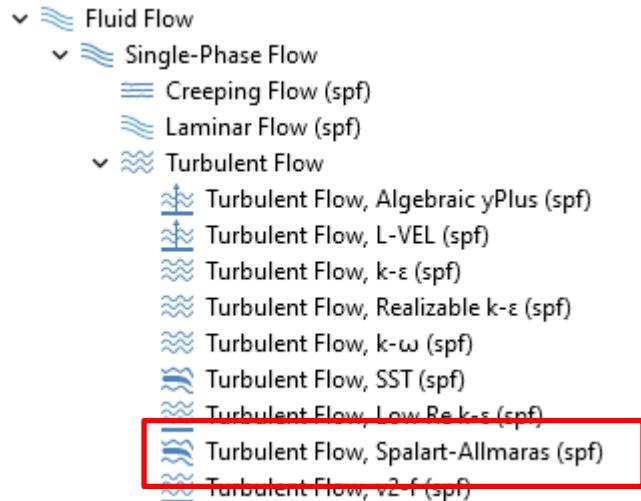


Tip angle = 45deg

Hub radius: 95mm, Blade length: 500mm, AoA change: 12deg

[1] A. Ahmed Shamol, S. Yaser Ahmed, M. A. Islam Shubho, and T. Rahman, "Design, analysis and fabrication of a fully articulated helicopter main rotor system," Journal of Mechanical Engineering, Automation and Control Systems, Vol. 2, No. 1, pp. 54-64, Jun. 2021, <https://doi.org/10.21595/jmeacs.2021.21933>

2. 프로젝트 과정



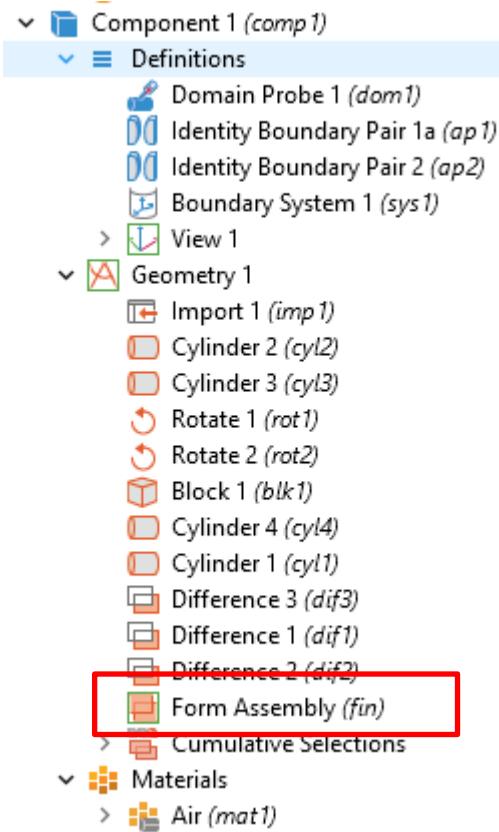
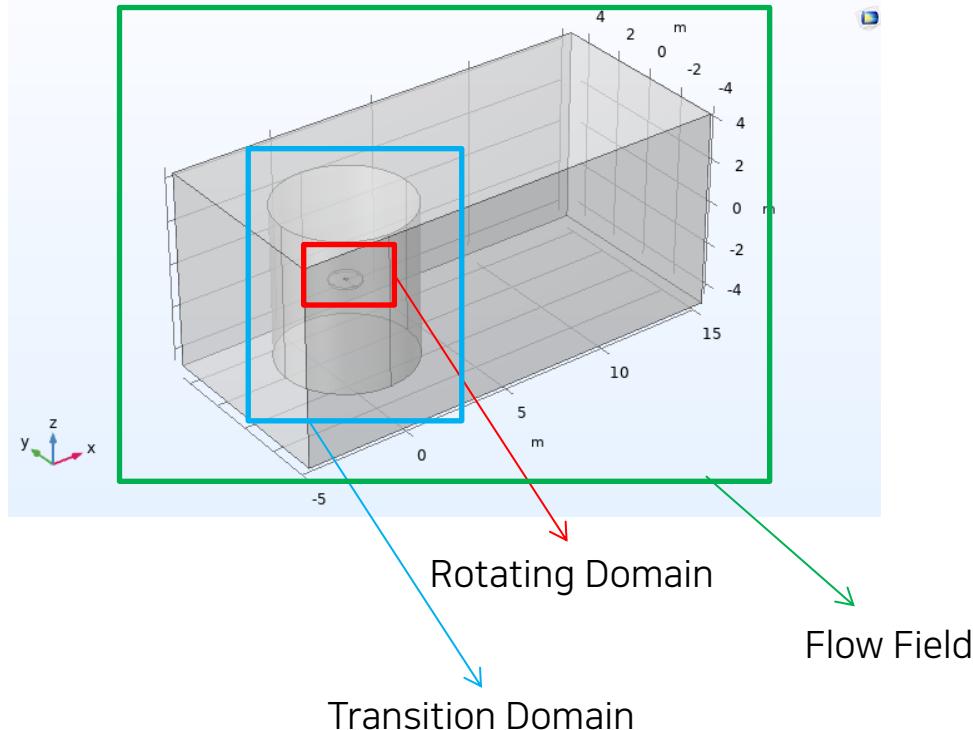
Single Phase Flow – Turbulent Flow - Spalart-Allmaras Turbulence model

Frozen Rotor 해석 후, Time Dependent에 대한 해석

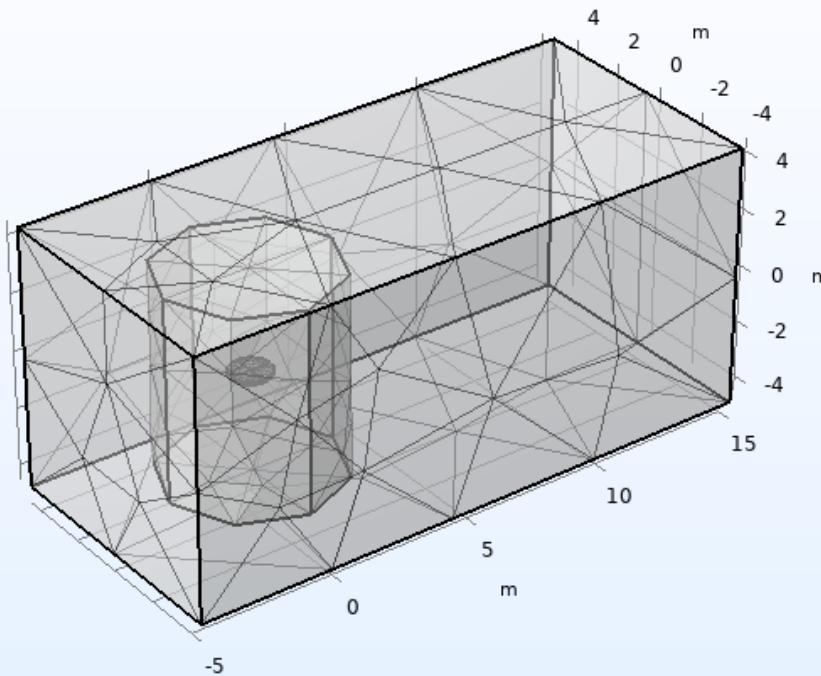
Aerodynamics 성능: 추력 계수 이용

Aeroacoustic 성능: SPL(Sound Pressure Level) 이용

2. 프로젝트 과정



2. 프로젝트 과정



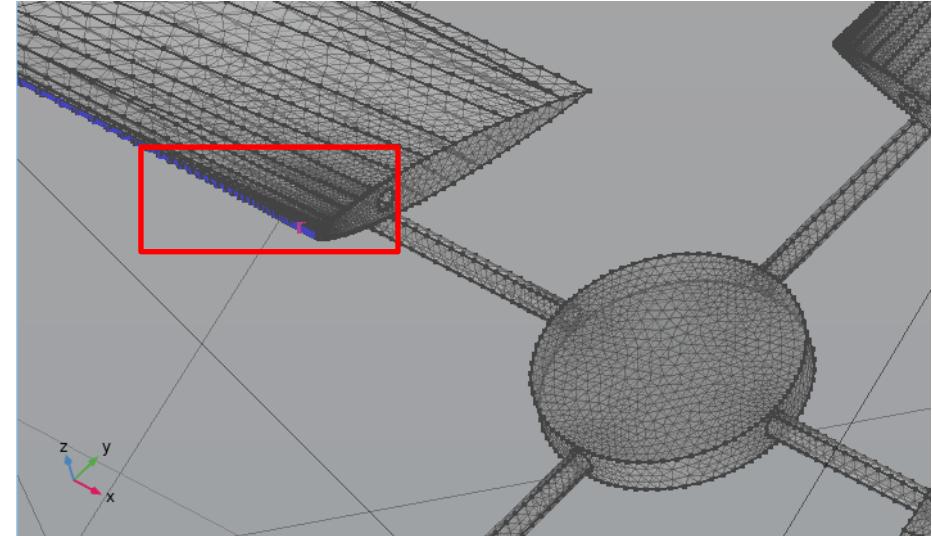
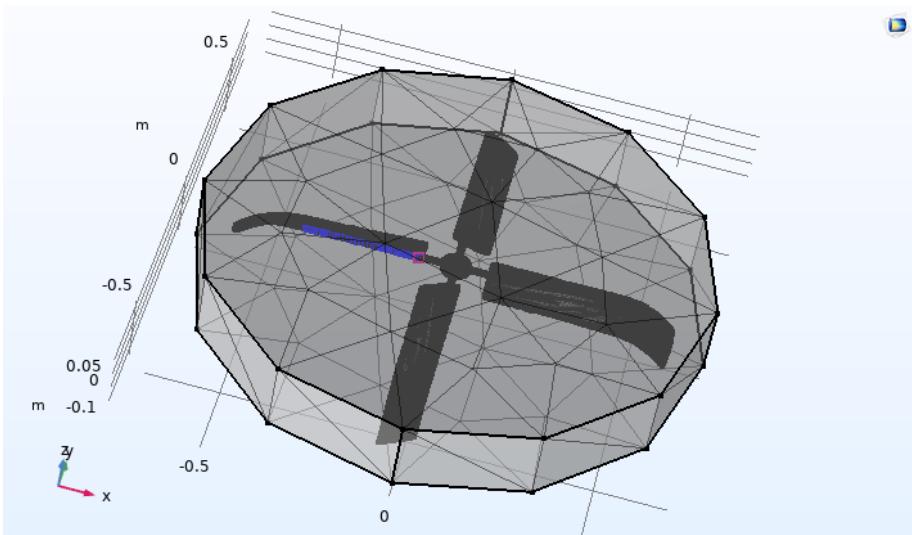
외부 Flow field: Coarse

내부 Rotating Domain: Fine

1. Deg0
총 141,312개의 Element
Average element quality: 0.5446
Solved DoF: 137,915

2. Deg20
총 1,134,796개의 Element
Average element quality: 0.5982
Solved DoF: 212,943

2. 프로젝트 과정



Extremely Fine하게 짠음에도 quality error 발생

-> deg45는 제외함.

Anhedral tip의 유무에 따른 성능 비교가 초점이 됨

2. 프로젝트 과정

- ▼  Turbulent Flow, Spalart-Allmaras (spf)
 -  Fluid Properties 1
 -  Initial Values 1
 -  Wall 1
 -  Flow Continuity 1
 -  Inlet 1
 -  Outlet 1
 -  Open Boundary 1
 -  Pressure Point Constraint 1

▼ Boundary Condition

Velocity

▼ Velocity

Normal inflow velocity
 Velocity field

U_0 40 m/s

▼ Turbulence Conditions

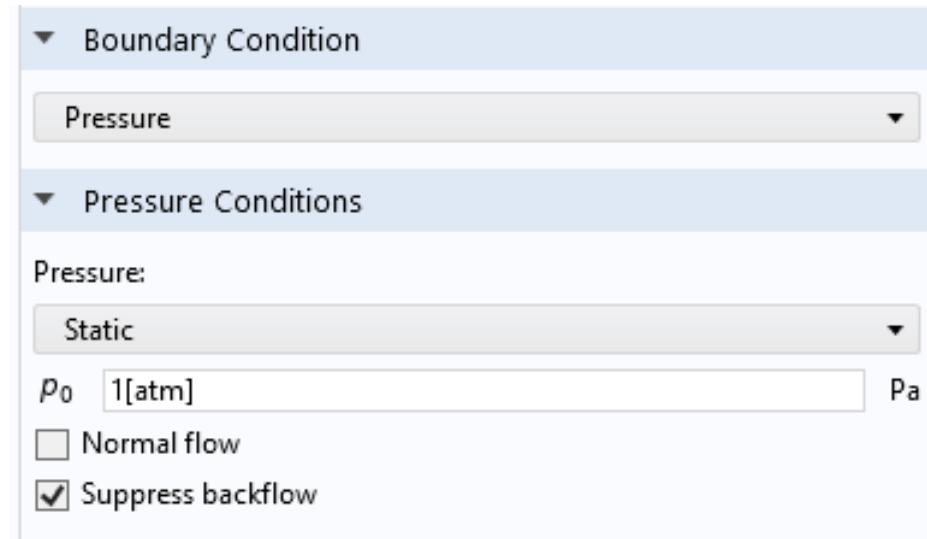
Undamped turbulent kinematic viscosity:

ν_0 $3*spf.nu$ m²/s

Inlet

2. 프로젝트 과정

- ▼ Turbulent Flow, Spalart-Allmaras (spf)
 - Fluid Properties 1
 - Initial Values 1
 - Wall 1
 - Flow Continuity 1
 - Inlet 1
 - Outlet 1
 - Open Boundary 1
 - Pressure Point Constraint 1



Outlet

2. 프로젝트 과정

- ▼  Turbulent Flow, Spalart-Allmaras (spf)
 -  Fluid Properties 1
 -  Initial Values 1
 -  Wall 1
 -  Flow Continuity 1
 -  Inlet 1
 -  Outlet 1
 -  Open Boundary 1
 -  Pressure Point Constraint 1

▼ Boundary Condition

Boundary condition:

No viscous stress

▼ Turbulence Conditions

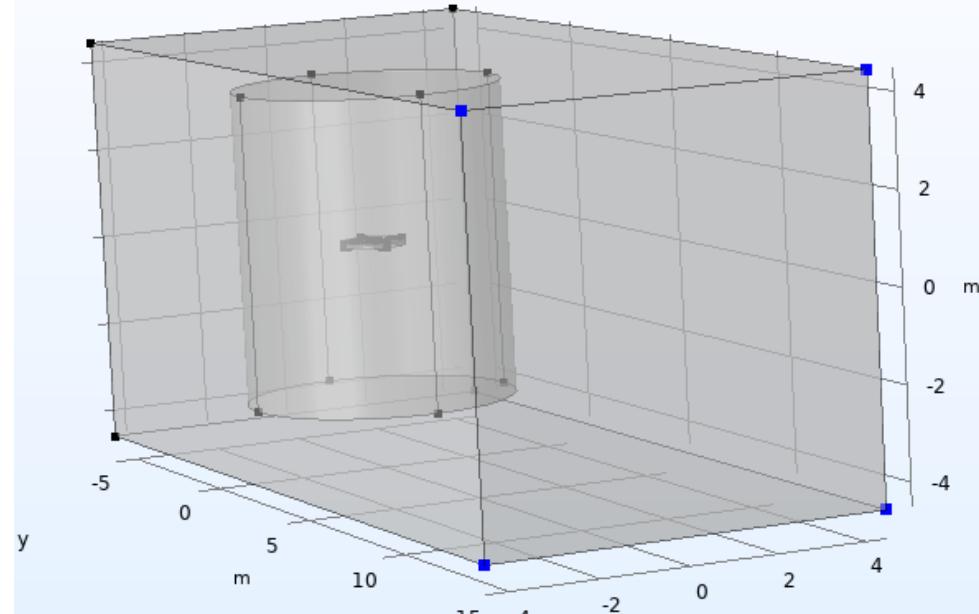
Undamped turbulent kinematic viscosity:

ν_0 m²/s

Open Boundary

2. 프로젝트 과정

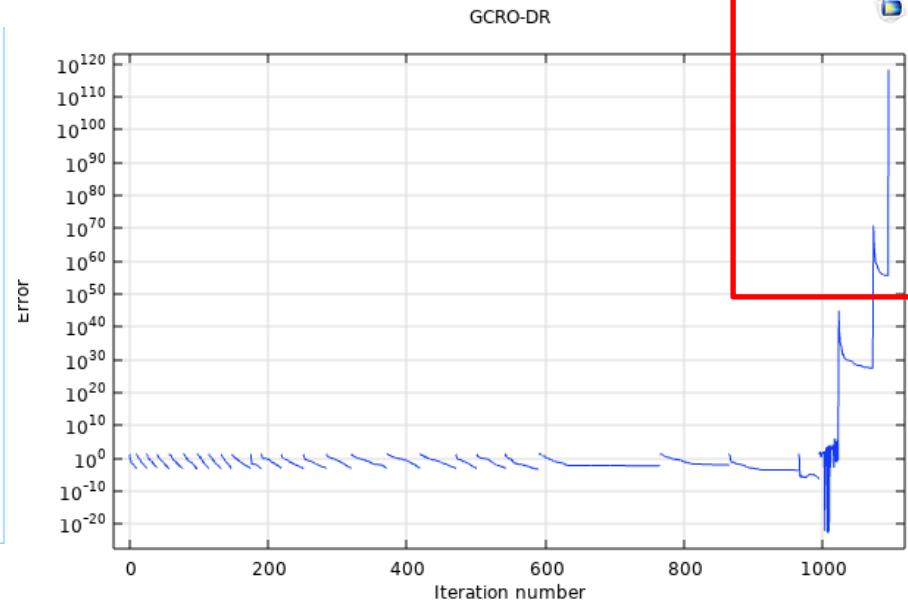
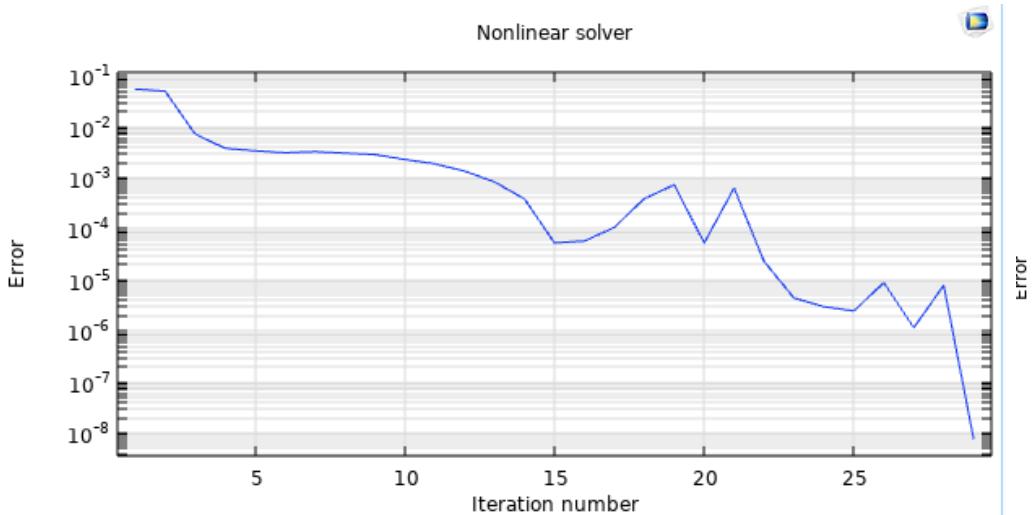
- ▼ Turbulent Flow, Spalart-Allmaras (spf)
 - Fluid Properties 1
 - Initial Values 1
 - Wall 1
 - Flow Continuity 1
 - Inlet 1
 - Outlet 1
 - Open Boundary 1
 - Pressure Point Constraint 1



Pressure Point Constraint: 1atm

이후 study!

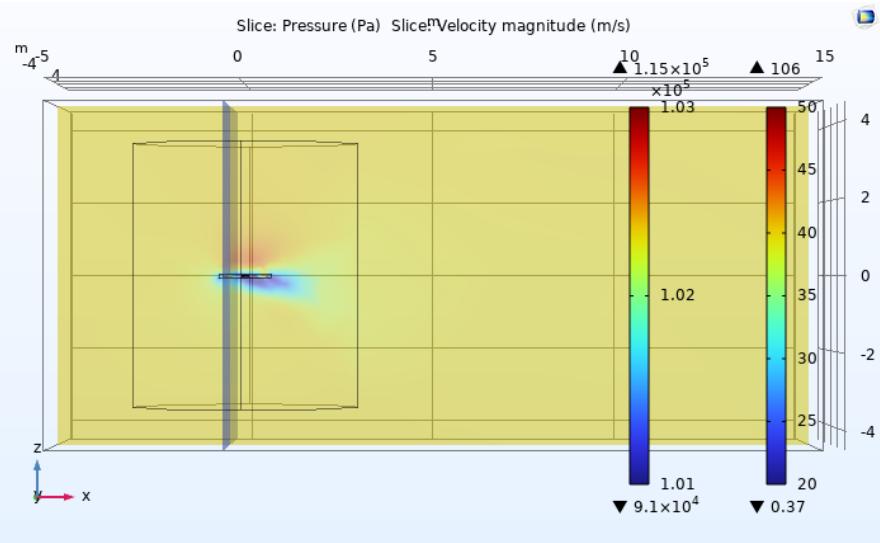
3. 프로젝트 결과



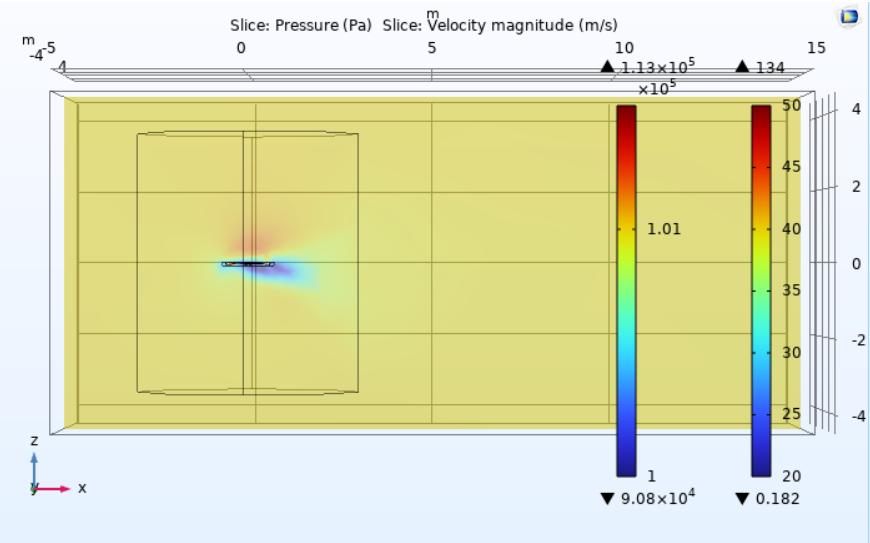
Iteration이 증가해도 GCRO-DR Error가 수렴하지 않는 문제가 제일 난관이었음

Max iteration을 늘리고, Relative Tolerence를 줄여서, 여러 가지 parameter의 조합으로 해석

3. 프로젝트 결과



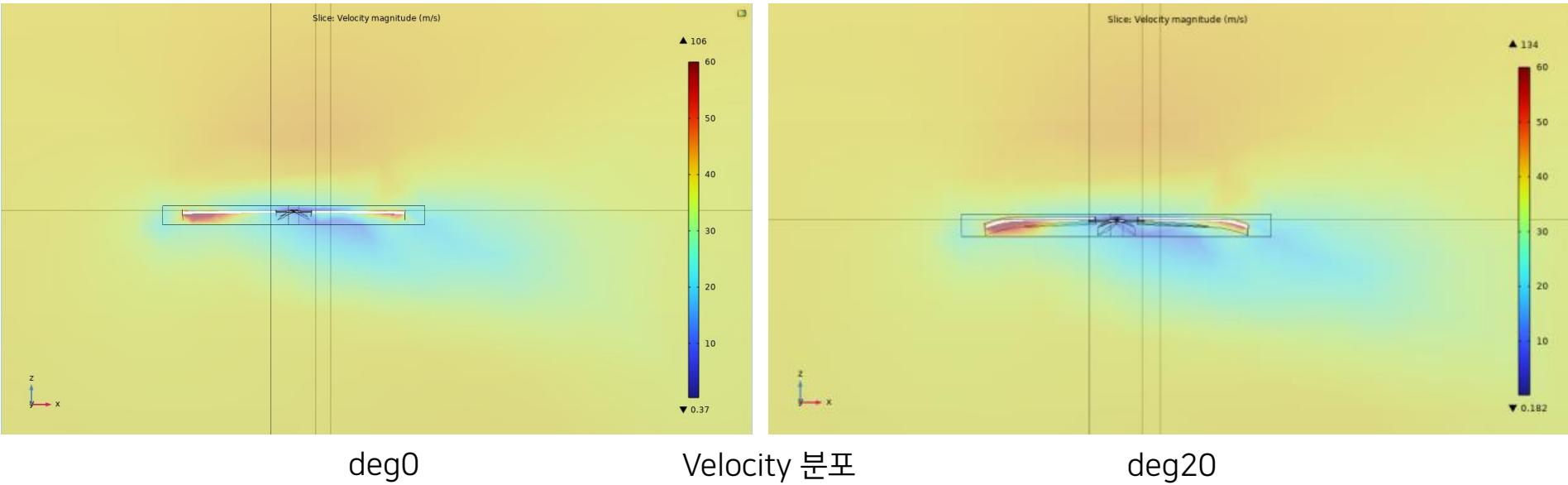
deg0



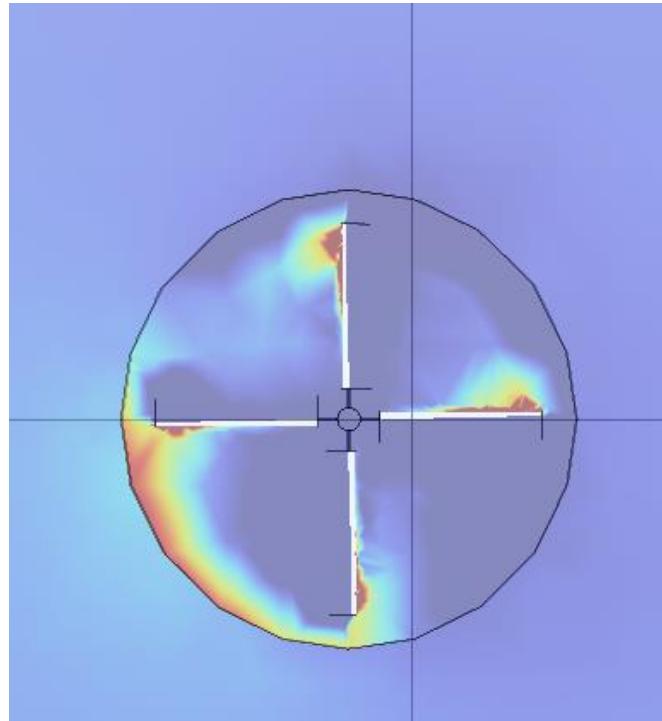
Velocity 분포

deg20

3. 프로젝트 결과

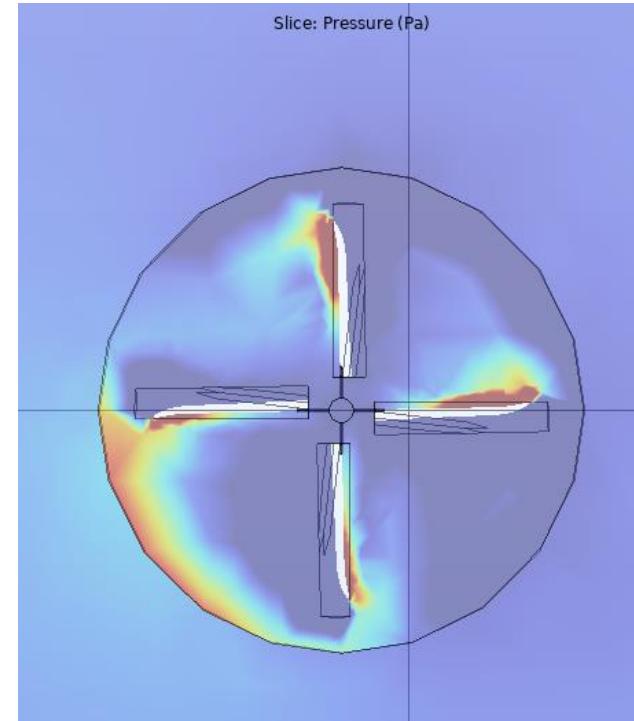


3. 프로젝트 결과



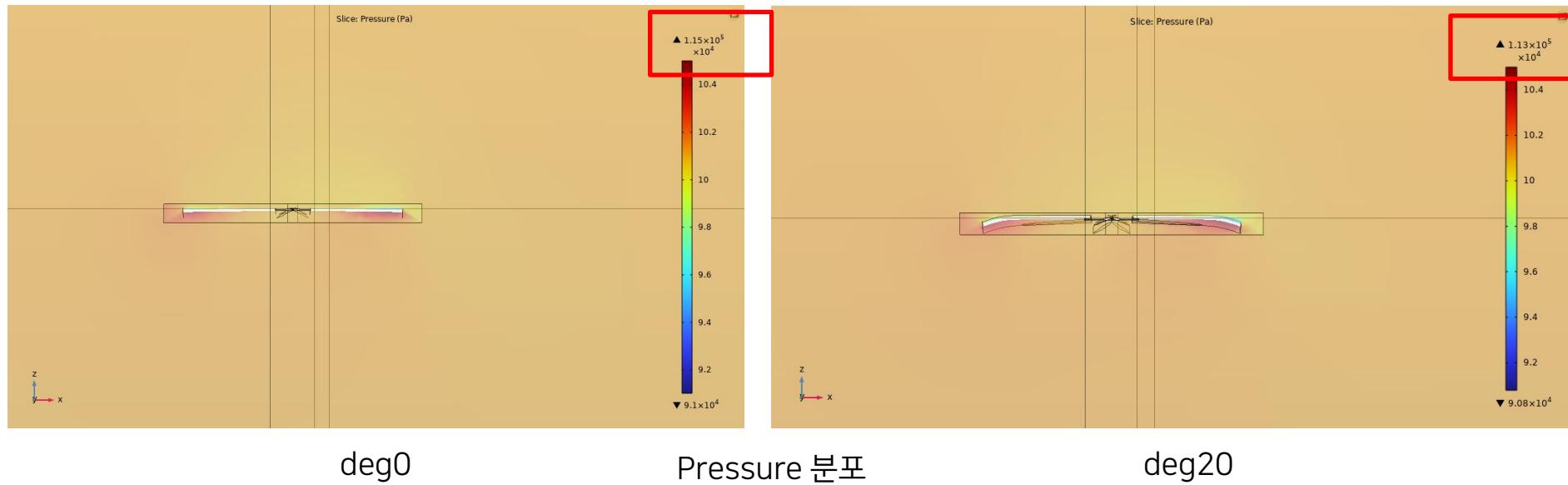
deg0

Velocity 분포



deg20

3. 프로젝트 결과



3. 프로젝트 결과

	deg0	deg20
Pressure (Max), (Pa)	1.154e5	1.132e5
Avg. Induced Velocity (m/s)	3.9712	3.5019
Thrust Force (N)	42.96	37.89
Thrust Coefficient	2.031e-3	1.792e-3

deg20에서 Pressure의 최댓값 감소 -> 전체적으로 완만해진 Pressure Contour

추력, 추력계수 측정은 Momentum Theory에 따른 공식 사용

$$C_T = \frac{T}{\rho A (\Omega R)^2}$$

$$T = 2\rho A v_i^2$$

각 기호의 의미

- T : 로터의 추력 (단위: N)
- ρ : 공기 밀도 (단위: kg/m³)
- A : 로터 디스크 면적 ($A = \pi R^2$, 단위: m²)
- Ω : 로터의 각속도 (단위: rad/s)
- R : 로터 블레이드의 반경 (단위: m)

각 기호의 의미:

- T : 로터의 추력 (N)
- ρ : 공기 밀도 (kg/m³)
- A : 로터 디스크 면적 ($A = \pi R^2$, m²)
- v_i : 유도속도(Induced Velocity) (m/s), 로터 디스크를 통과하는 유속의 평균값

3. 프로젝트 결과

[1]*

Table 3. Viscous model: Spalart-Allmaras (Eq. (1))

θ	RPM	Tip velocity	Thrust on blade	Thrust on plane below blades (100 mm)	Torque
5	50	3.58 m/s	0.0522478 [N]	0.019456 [N]	0.0079284 [N m]

deg0의 Reference

RPM, Blade의 수를 변환하여 Thrust force를 계산하면:

20.90N

주요 차이 이유

Thrust Force (N)	42.96
------------------	-------

- 1) 위의 ref에서는 받음각이 0도지만, 본 프로젝트에서는 20 + 12도의 받음각
-> 추력 상승

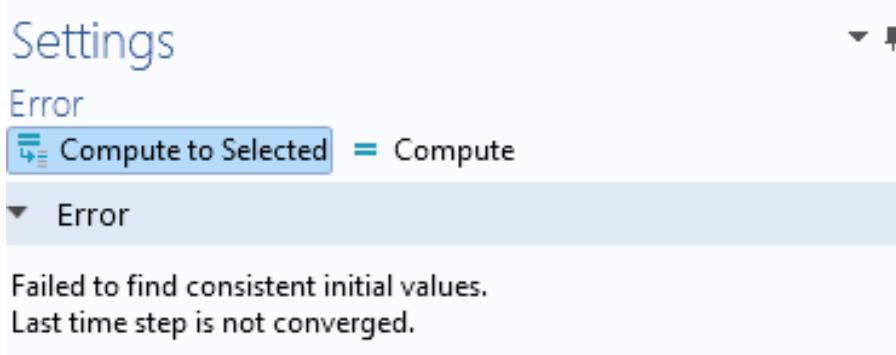
Result 1) Tip에 의해 Thrust Coefficient가 11.8% 감소
공력 성능은 감소

3. 프로젝트 결과

Aeroacoustic 성능 분석을 위해서는 Frequency Domain의 해석 필요



그러기 위해서는 Time Dependent에서의 해석 필요



Error가 발생하는 문제 발생,

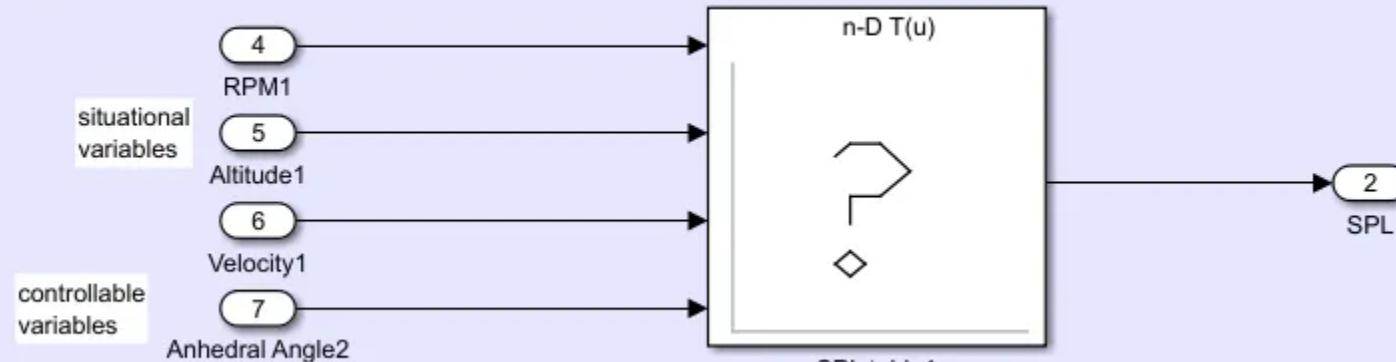
결국 Time Dependent에 대해서는 해석 실패



3. 프로젝트 결과

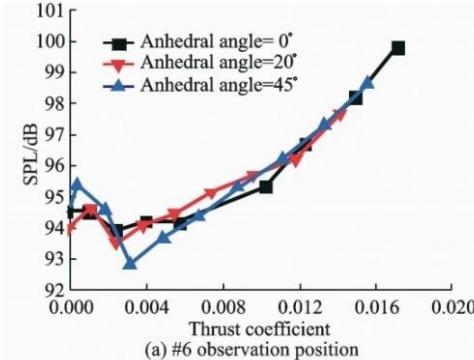
Time data 없이 SPL을 근사적으로 구할 수 있는 Method?

COMSOL

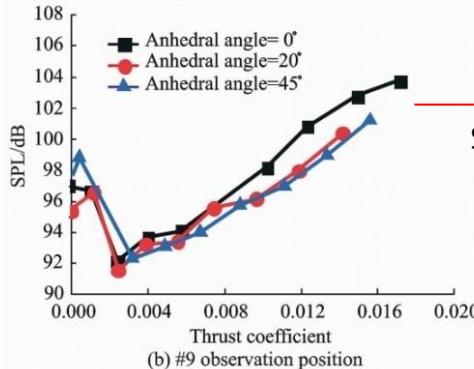


3. 프로젝트 결과

[1]*



(a) #6 observation position

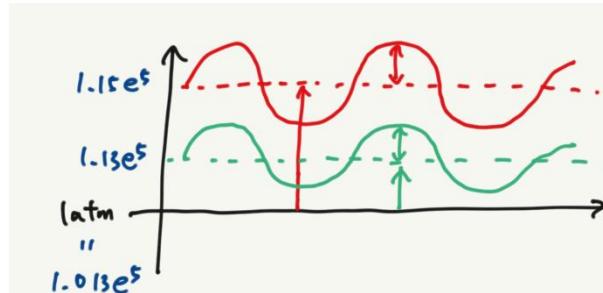


(b) #9 observation position

선행 연구에서는
SPL 약 3dB(3%)의 차이 발생했다는 결과

Fig. 9 Comparison of SPL among four-bladed rotors with different blade-tip anhedral angles

$$\boxed{\text{SPL} = 20 \log_{10} \left(\frac{P_{RMS}}{20 \times 10^{-6}} \right)}$$



가정: 압력의 최댓값과 대기압의 차이가
압력 변동값에 비례한다고 가정!



Result 2) Tip에 의해 SPL이 1.38dB 감소함!

Limitation?