

무격자기법 기반의 유동해석 솔버를 이용한 초음속유동에서의 그리드핀 해석

CFD Analysis of Grid-Fin in Supersonic Flow using Meshless Based Flow Solver

최대산*, 김성태, 이상돈

(주)넥스트폼 기술연구소



목차

I. 연구배경	3p
II. 연구방법	9p
III. 해석결과	16p
IV. 결론	21p

I. 연구배경

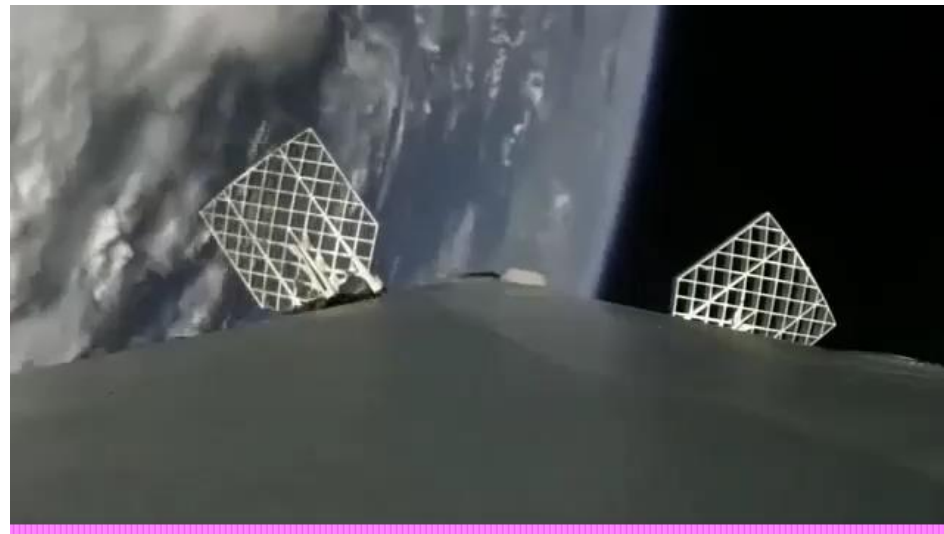
1. 그리드핀
2. 그리드핀 연구 동향
3. 연구 목표

■ 그리드핀

- 핀의 내부에 web이 교차하는 격자 형상의 조종면
 - Frame, Cell(Web), Support
- 1970년대 소련에서 air-break 및 비행 안정성 향상을 위해 처음으로 사용
- 군사적 목적, 우주 발사체에 활용
 - Soviet SS series, MOAB, Vympel R-77, Soyuz, SpaceX Falcon 9 등



<Grid-Fin of MOAB>



<SpaceX's First-stage landing>

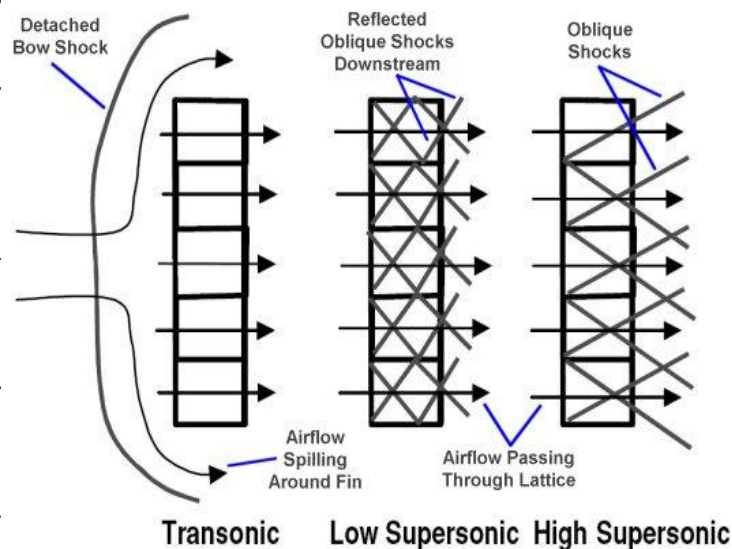
■ 그리드핀

■ 그리드핀 특성

- 공력 : (1) 고반음각 **실속특성 우수**, (2) **압력중심 변화 작음**, (3) **항력 극대화 가능**
- 구조 : 특히 고속에서 (1) **힌지 모멘트**, (2) **공력가열** 감소 유리
- 설계 및 활용 : 접힌 상태에서 발사 가능하므로 **보관성 및 발사의 편의성** 증대
- 그리드핀은 유동특성이 **속도(마하수)**에 따라 크게 변화

<Flow characteristics of a Grid-Fin>

Flow regime	Flow form	Mach number	Characteristics
Subsonic	Simple flow	0 < M < 0.8	<ul style="list-style-type: none"> No flow with complicated characteristics occurs Same as flat plate pin analysis
Transonic	Chocked flow	Mc1 < M < 1	<ul style="list-style-type: none"> Internal flow can be modeled as converting nozzle Chocking occurs and the drag increases greatly Hinge moment greatly increased Control efficiency lower than plate wing
	Bow shock	1 < M < Mc2	<ul style="list-style-type: none"> High drag due to shock wave Hinge moment greatly increased Control efficiency lower than plate wing
Supersonic	Reflecting shock wave	Mc2 < M < Mc3	<ul style="list-style-type: none"> Shockwave attaches to the front end, and reflection shock wave occurs Reduced lift due to compressed air and expanded air
	Non-reflecting shock wave	Mc3 < M	<ul style="list-style-type: none"> Non-reflective shock wave generation due to small attachm ent angle The most appropriate form



<Schematic of flow characteristics of a Grid-Fin>

■ 그리드핀 관련 연구 동향

■ 형상 관련 연구

- 주로 그리드핀 형상 변수에 따른 공력 특성 연구
- 핀 사이즈, 내부 Cell 개수 및 모양, Cell / Frame 단면 등

<List of literatures on Grid-fin configuration>

Year	Title	Geometric parameter	method
2019	그리드핀을 적용한 작은 세장비를 갖는 자탄의 천음속 공력특성 전산해석	• Cell : thickness	CFD
2019	Experimental analysis of cell pattern on grid fin aerodynamics in supersonic flow	• Cell : pattern, Number of cell	Exp.
2015	Design of a grid fin aerodynamic control device for transonic flight regime	• Fin : Span, Height, Thickness • Cell : Depth, Height/Width, Leading edge sharpness, Sweep angle	CFD
2014	Integration of grid fin for the optimal design of missile systems	• Fin alone : Span, Height • Cell : Depth, Number of cell • BT : Position, Support configuration	Analytic
2012	Drag reduction for sweptback grid fin with blunt and sharp leading edges	• Cell : Leading edge sharpness, Sweep angle	CFD
2007	Effect of geometric parameters on the aerodynamic characteristics of grid-fin cells at supersonic speeds	• Cell : Depth, Height/Width, Thickness	CFD
2005	The research analysis of aerodynamic numerical simulation of grid fin	• Cell : Section configuration, Thickness, Number of cell	CFD
2004	Grid pattern effects on aerodynamic characteristics of grid fins	• Cell : Pattern	Exp.
1998	Computation of flows past grid fin missiles	• Fin : Sweep angle	CFD
1994	An experimental investigation of grid fin drag reduction techniques	• Fin : Thickness • Frame : Section configuration, Height/Width	Exp.
1993	Curvature and leading edge sweep back effects on grid fin aerodynamic characteristics	• Fin : Curvature • BT : Sweep angle	Exp.

■ 그리드핀 관련 연구 동향

■ Exp. vs. CFD

- CFD 연구 검증 실험 데이터
- 검증 결과 : (초음속) Exp. 와 CFD 최대 ~10% 내외 차이

<List of experimental literatures used for CFD verification>

Year	Title	Author	Institute
2001	Wind Tunnel Investigation of Grid Fin and Conventional Planar Control Surfaces	Fournier, E. et al.	Defence Research Establishment Valcartier (DREV)
1997	A Preliminary Analysis of the DERA Lattice Controls Database	Simpson, G. et al.	The Defence Evaluation and Research Agency (DERA)
1994	An Experimental Investigation of Grid Fin Drag Reduction Techniques	Miller, M. S. et al.	The National Testing Service (NTS)

<List of literatures on Exp. and CFD analysis on Grid-fin>

Year	Title	Exp. reference	Maximum Difference between Exp.	Object
2019	Numerical simulation of aerodynamic characteristics and heating for grid fin missiles	DREV	Normal – 5 % / Axial – 8 %	BT
2018	Simplified Numerical Approach for the Prediction of Aerodynamic Forces on Grid Fins	NTS	Normal – 15 % / Axial – n/a	GF
2003	Navier–Stokes Computations for Body/Cruciform Grid Fin Configuration	NTS	Normal – 5 % / Axial – 20 %	GF
2003	Numerical Investigation of Canard-Controlled Missile with Planar and Grid Fins	DREV	Normal – 10 % / Axial – 15 %	BT
2001	Computational Fluid Dynamics Analysis of a Missile with Grid Fins	DERA	Fluent : Normal – 7 % / Axial – 11 % In-house : Normal – 13 % / Axial – 50 % ↑	BT
2001	Viscous CFD Calculations of Grid Fin Missile Aerodynamics in the Supersonic Flow Regime	DERA	Normal – 17 % / Axial – 9 %	BT

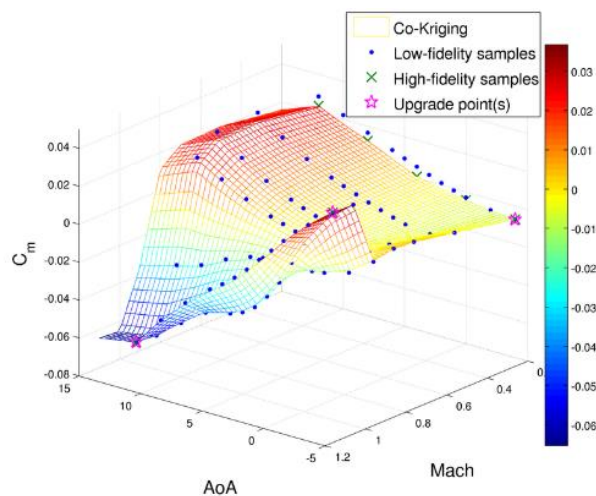
■ 연구목표

■ 그리드핀 형상/유동 변수에 따른 6분력 공력 DB 구축

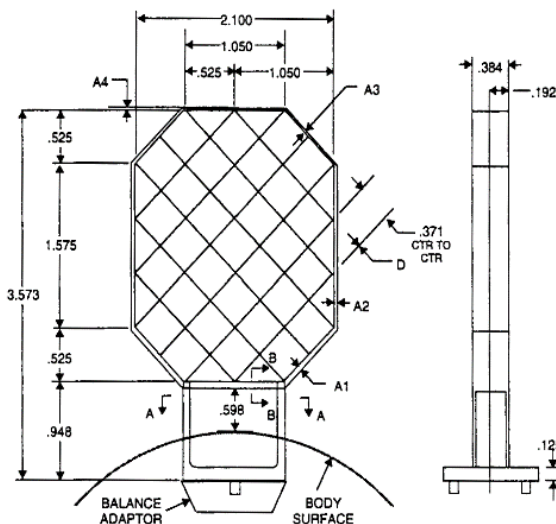
- 형상 관련 22 개, 유동조건 관련 4 개 변수
- 그리드핀 단독, 그리드핀 셀, BT(Body-Tail)
- 민감도 분석, Body effect, scaling effect 분석 등

■ 본 발표에서는,

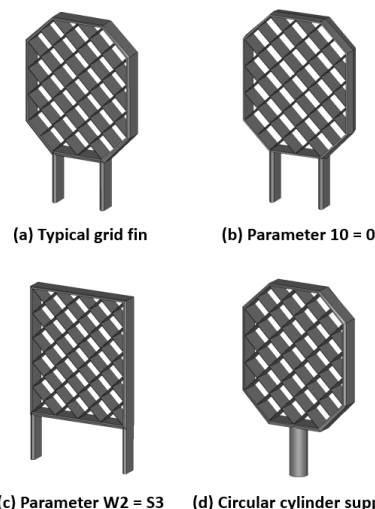
- 무격자기법 기반의 유동해석 솔버(FAMUS)를 이용, **초음속 그리드핀의 Benchmark 유동해석** 수행
- 해석 결과로 얻어진 공력계수 데이터를 **실험 데이터와 비교**를 통해 솔버의 해석 정확도 확인



<Example of Kriging model for Aerodynamic coefficient>



<Parameters of Grid-Fin configuration>



<Various Grid-Fin configuration>

II. 연구방법

1. 무격자기법 기반의 유동해석 솔버
2. 지배방정식 및 수치해석 기법
3. Benchmark

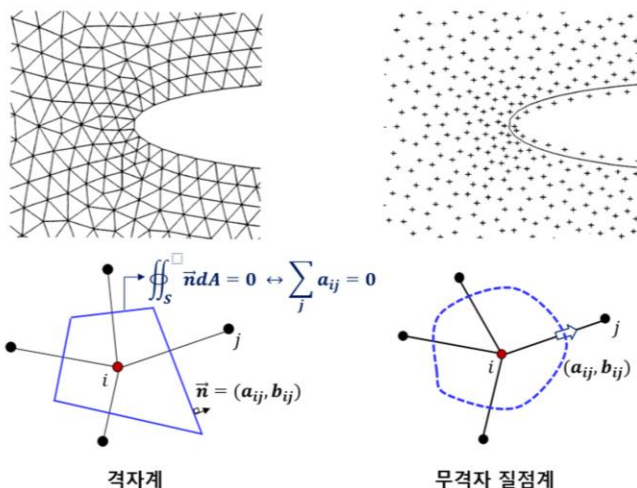
■ 무격자기법 기반의 유동해석 솔버

■ 무격자기법 특징

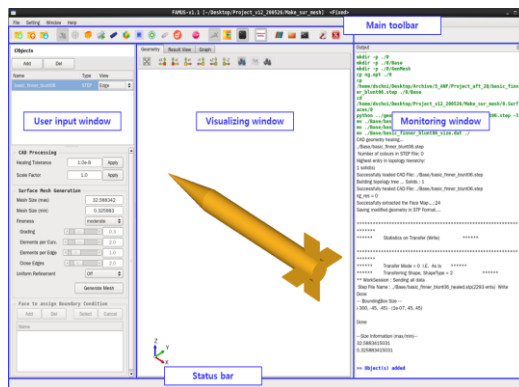
- 주변 질점 이용 gradient 계산 (\leftrightarrow Green-Gauss gradient)
 - LSM : 기준점과 주변 질점간 근사함수(Taylor series)의 truncation error 기준
 - 과도한 계산을 요구하는 Flux conservation 대신, Geometric conservation을 제약조건(GC-LSM)으로 추가 \rightarrow 보존성 문제 해소
- 질점만을 사용하기 때문에, 해석 형상에 유연하게 대처 가능

■ FAMUS(Fully Automated MULTI-physics Simulation)

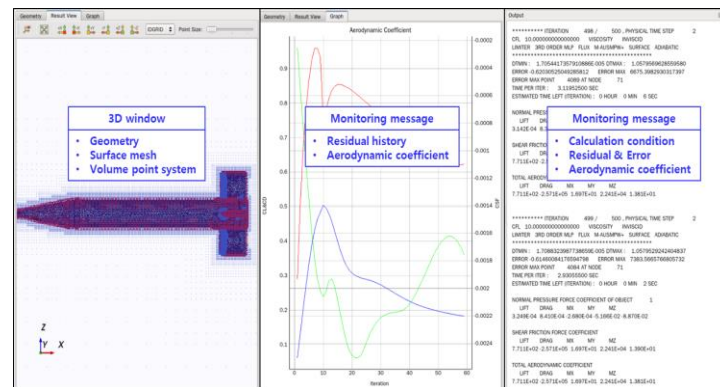
- 무격자 기법 기반의 해석 솔버 + 오픈 소스 라이브러리
- 전 과정 파라미터 기반으로 작동 방식 \rightarrow 전처리 과정 사용자 개입 최소화 \rightarrow 자동화 유리



<Concept of FVM and Meshless>



<FAMUS User Interface>



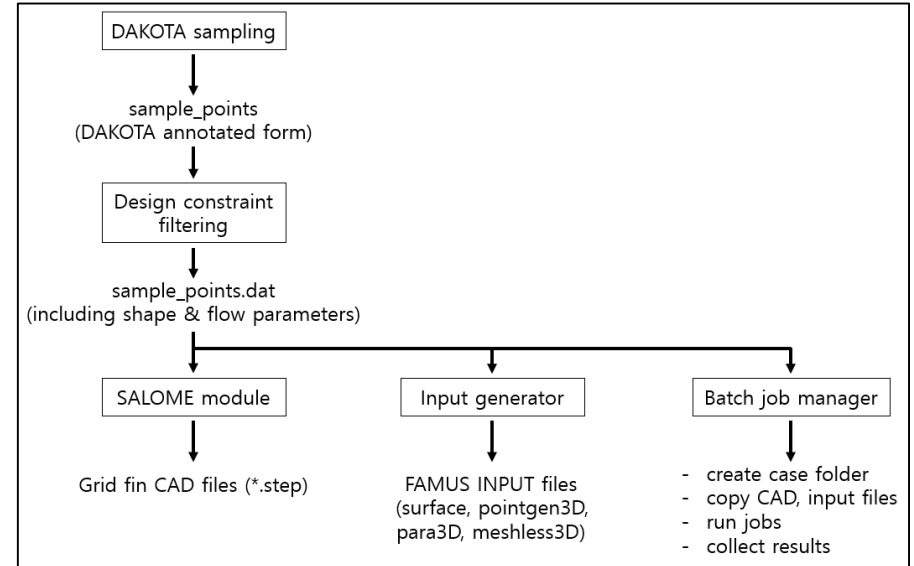
■ 무격자기법 기반의 유동해석 솔버

■ 다수 케이스 유동 해석 절차

- (사용자) DB 구축 파라미터 범위, 샘플링 개수 결정 → DAKOTA – DOE distribution 생성
- (자동) Grid-Fin CAD 파일 자동 생성 모듈 → CAD 파일 생성
- (자동) FAMUS 솔버 인풋 및 해석 질점 생성 → 유동해석
- 신속하게 다수 케이스 유동 해석 수행 가능
 - (과제 초기 단계) 100 케이스 setup : 70 케이스 성공 / 15 케이스 minor / 15 케이스 해석 질점 생성 실패
 - 모든 케이스에 사용자 개입 vs. 예외적 상황에 사용자 개입

1	%eval_id	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	AOA	CONSTRAINT1	CONSTRAINT2	PASS	
2	36	1.358521	4.312715	0.457288	0.057309	0.064537	0.094418	0.042023	0.013364	0.343703	0.061423		5	1	1	O
3	142	4.802519	4.52626	0.459034	0.081238	0.091522	0.089523	0.055348	0.030588	0.232746	0.134862		0	1	1	O
4	149	2.305782	4.524005	0.495277	0.067325	0.096021	0.021259	0.010518	0.015206	0.046932	0.202484		0	1	1	O
5	179	3.428137	3.581385	0.461668	0.0987	0.092568	0.07523	0.024592	0.016848	0.105689	0.268959		15	1	1	O
6	215	3.071106	2.783114	0.217093	0.09292	0.08531	0.095972	0.071463	0.064148	0.12811	0.035333		15	1	1	O
7	231	4.315644	3.01271	0.235191	0.057273	0.079603	0.049309	0.027803	0.042611	0.05123	0.160915		0	1	1	O
8	250	4.047934	3.910126	0.447412	0.06808	0.051557	0.098358	0.014863	0.015627	0.051772	0.135996		5	1	1	O
9	257	4.69499	3.783849	0.421034	0.078432	0.050995	0.044838	0.028571	0.029124	0.102551	0.185869		15	1	1	O
10	271	4.734785	4.813385	0.49258	0.097904	0.094781	0.095192	0.052124	0.050417	0.369071	0.075152		10	1	1	O
11	285	1.641288	4.228526	0.340242	0.080388	0.096178	0.071128	0.015971	0.015569	0.013413	0.31011		10	1	1	O
12	290	2.041062	3.116923	0.240788	0.097136	0.081622	0.086963	0.055161	0.079669	0.017428	0.18862		15	1	1	O
118	1	2.156525	1.887038	0.25738	0.051177	0.02155	0.0963	0.047124	0.097456	0.467691	0.286732		0	0	0	X
119	2	1.762292	2.913251	0.384119	0.095087	0.022301	0.051068	0.076381	0.020496	0.305909	0.011881		0	0	1	X
120	3	1.899185	4.39357	0.448534	0.056202	0.015652	0.097166	0.057094	0.049645	0.03901	0.282349		0	0	1	X
121	4	3.817667	2.410824	0.271671	0.073043	0.049016	0.090256	0.064843	0.078897	0.404657	0.041895		5	0	0	X
122	5	2.834848	1.296231	0.254276	0.057153	0.063339	0.084802	0.052439	0.014299	0.481461	0.000173		5	1	0	X
123	6	1.417054	4.751818	0.303113	0.082199	0.025156	0.096856	0.033197	0.018872	0.307147	0.024723		10	0	0	X
124	7	3.537979	4.044678	0.313291	0.045971	0.022318	0.064914	0.041041	0.082252	0.03958	0.215741		10	0	1	X
125	8	1.339893	1.989283	0.298073	0.046877	0.079123	0.034504	0.024526	0.054469	0.083169	0.473421		15	0	0	X
126	9	3.270241	1.582544	0.368691	0.040567	0.048213	0.084263	0.020571	0.09037	0.138877	0.482061		15	0	0	X
127	10	2.391967	3.314851	0.231387	0.042304	0.037369	0.033546	0.01729	0.020691	0.093792	0.240325		5	1	0	X
128	11	4.580775	1.125367	0.335408	0.046568	0.045056	0.078083	0.07856	0.071384	0.197856	0.141152		15	0	0	X
129	12	3.932236	1.349635	0.463679	0.01007	0.099683	0.057971	0.017709	0.088351	0.026214	0.09043		15	0	1	X
130	13	2.282655	1.69073	0.227575	0.011324	0.0461	0.069126	0.05271	0.044598	0.405852	0.42572		15	0	0	X
131	14	3.369273	2.299464	0.348568	0.070222	0.091962	0.032363	0.032086	0.092054	0.490534	0.196164		5	0	0	X
132	15	3.680417	2.732818	0.214305	0.01451	0.047407	0.096274	0.067861	0.021226	0.262793	0.225814		0	0	0	X
133	16	2.809538	1.080367	0.369431	0.047871	0.067545	0.044981	0.044589	0.08147	0.114591	0.068487		10	0	1	X
134	17	1.779939	4.09453	0.294286	0.067007	0.073894	0.026774	0.084008	0.062974	0.138782	0.27192		0	0	0	X

<Sampling parameters for solver setup>



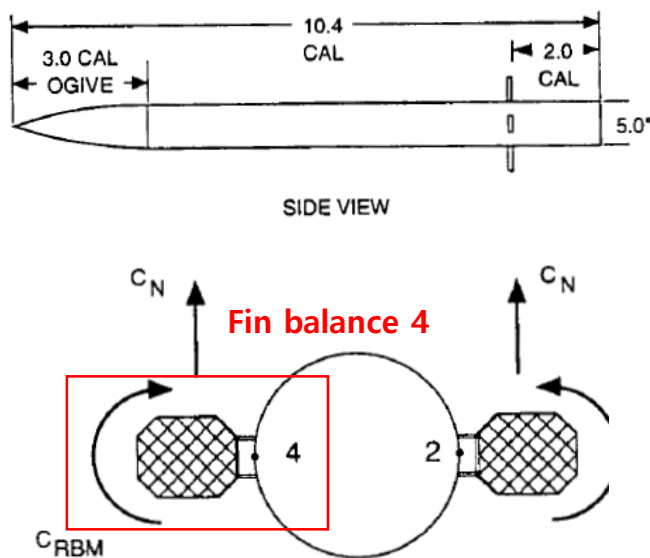
<Flow chart of automated sampling point calculation>

■ Benchmark

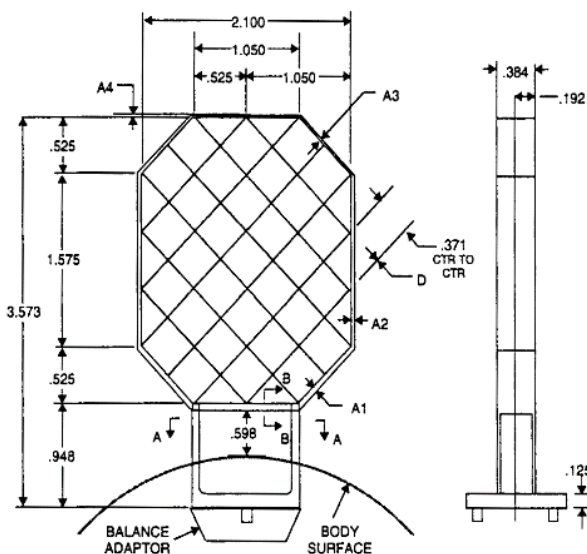
■ 참고문헌

- Mark S. Miller et al, “An experimental investigation of grid fin drag reduction techniques”, 1994
- 그리드핀 단독 공력계수 실험 데이터 (Mach 0.5 ~ 2.5)
- Data reduction model : Body + Grid-fin \times 2

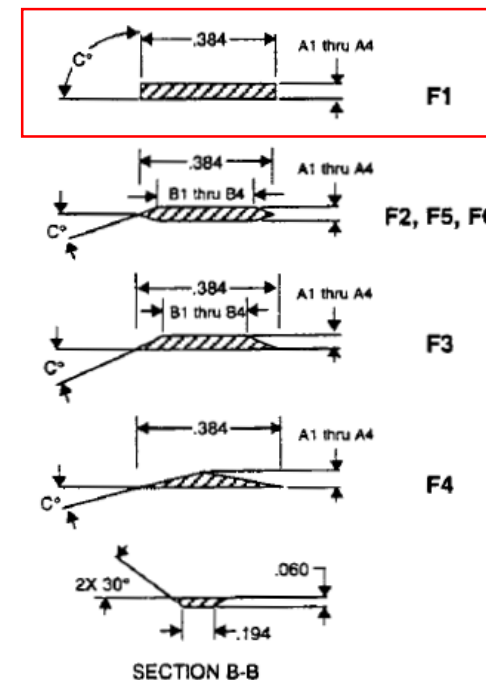
■ 문헌의 “F1” 형상 / Mach 1.8



<Wind tunnel BT model>



<Benchmark Grid-Fin Configuration>



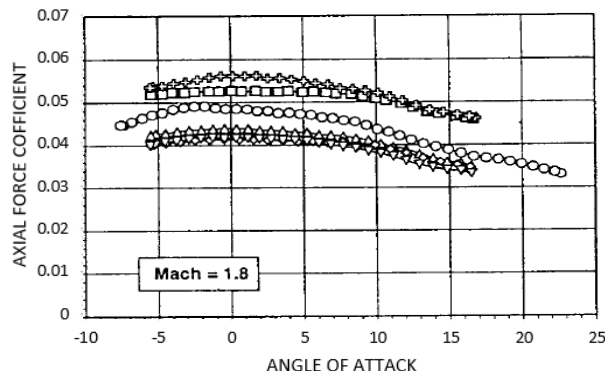
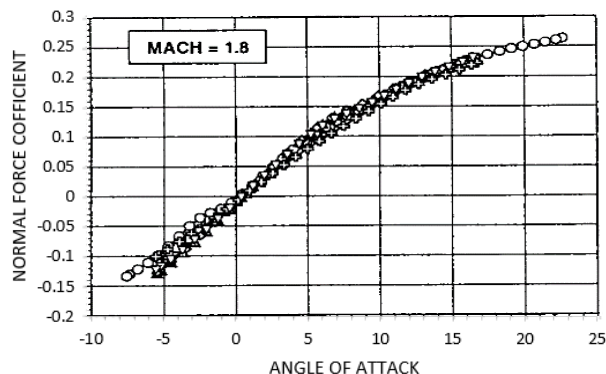
■ Benchmark

■ 계산조건 및 공력데이터 추출

- 실험 데이터 수치 공개 X / 그래프로 데이터 제공
- 공력계수 : 그림으로부터 데이터 추출 후, 사이 값 선형 보간
- 그림으로부터 추출 시 발생하는 오차 최대 $\pm 10\%$ 정도 (Normal force - AOA 5 도)

<Freestream condition and reference values for aerodynamic coefficient>

Freestream condition	<ul style="list-style-type: none"> • Mach number : 1.8 • Static pressure : 29647.47 (Pa) • Static temperature : 175.56 (K) • Re/L : 24.15 ($\times 10^6/m$)
Reference values	<ul style="list-style-type: none"> • Ref. area : 0.01267 (m²) • Ref. length : 0.127 (m) • Model length : 1.3208 (m) • Moment ref. center : 0.6604 (m)



<Experimental aerodynamic coefficient>

AOA	Normal	Axial
0	-0.0099	0.0526
5	0.0938	0.0523
10	0.1598	0.0507
15	0.2143	0.0468

<Experimental data of Benchmark case of Mach 1.8>

■ 지배방정식 및 수치해석 기법

■ 3D RANS equation

- Mass, momentum, energy balance

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_j)}{\partial x_j} = 0$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j + p \delta_{ij})}{\partial x_j} = \frac{\partial \tau_{ji}}{\partial x_j}, \quad \tau_{ij} = -\frac{2}{3} \mu \frac{\partial u_k}{\partial x_k} \delta_{ij} + \mu \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right)$$

$$\frac{\partial \rho e_t}{\partial t} + \frac{\partial[(\rho e_t + p)u_j]}{\partial x_j} = \frac{\partial \Omega_j}{\partial x_j}, \quad \Omega_i = u_j \tau_{ij} + k \frac{\partial T}{\partial x_i}$$

- Ideal gas, total energy definition

$$p = \rho R T, \quad R = 267.15 \text{ J/kg} \cdot \text{K}, \quad \gamma = 1.4$$

$$e_t = \frac{p}{\rho(\gamma - 1)} + \frac{1}{2} u_k u_k$$

- Viscosity and thermal conductivity

$$\mu = \mu_L + \mu_T, \quad k = k_L + k_T$$

$$k_L = \mu_L \frac{C_p}{Pr_L}, \quad k_T = \mu_T \frac{C_p}{Pr_T}, \quad Pr_L = 0.72, \quad Pr_T = 0.9$$

■ 지배방정식 및 수치해석 기법

■ Turbulence modeling

- $k - \omega$ SST model – 2003 Menter

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_j)}{\partial x_j} = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta^* \rho k \omega + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right]$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho \omega u_j)}{\partial x_j} = \frac{\gamma}{\nu_t} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] + 2\sigma(1 - F_1)\sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}$$

$$\nu_t = \frac{\alpha_1 k}{\max(\alpha_1 \omega, \Omega F_2)}$$

■ Numerical scheme

<Numerical scheme>

Governing equation	NS equation
Convective Flux scheme	M-AUSMPW+
Spatial reconstruction	MLP 3 RD
Turbulence model	$k - \omega$ SST, Menter 2003
Convective flux scheme	M-AUSMPW+
Spatial reconstruction	First order
Wall function	Standard wall function
Time integration	LU-SGS

Ⅲ. 해석결과

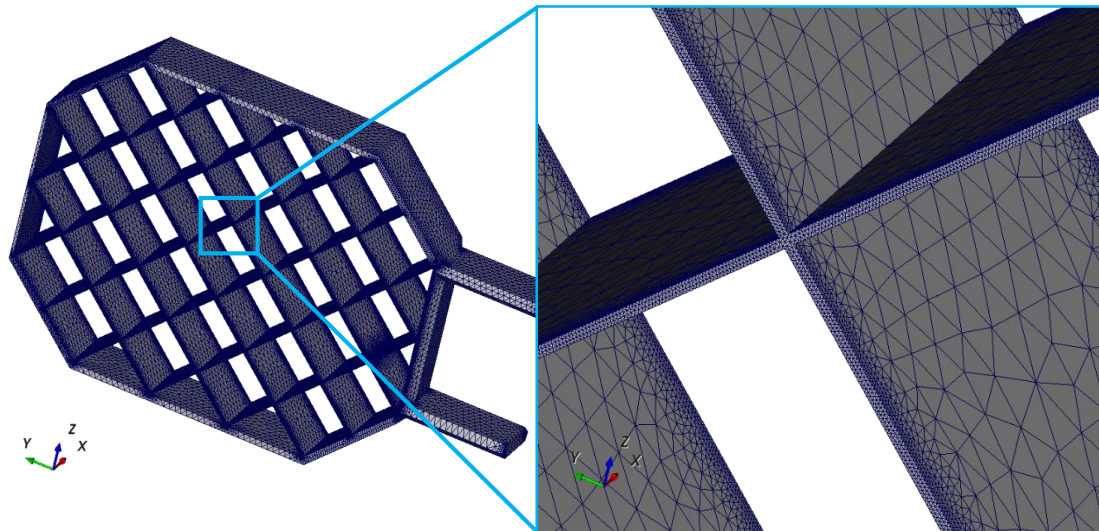
1. 해석 질점
2. 유동 분포
3. 공력 계수

해석결과

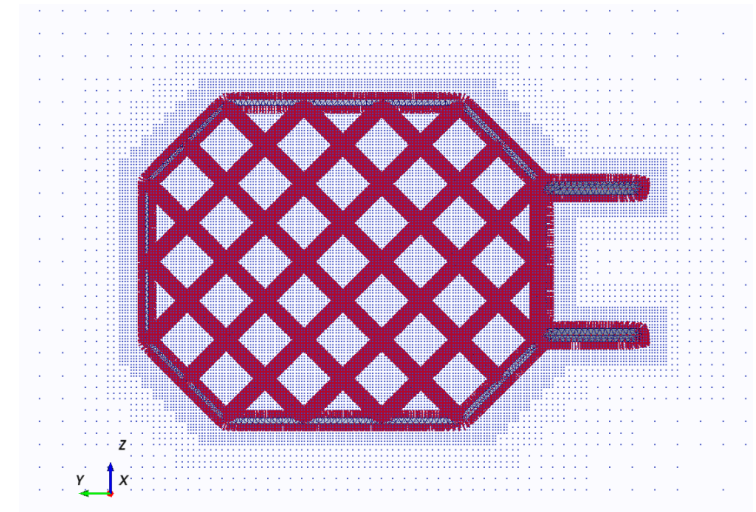
- 해석 질점
 - 해석 질점 정보

<Point system information>

Surface point	# surface point	253,744 (507,488)
	# elements across face-edge	2
Prism layer	Y+	40
	First height	0.00004
	# prism layer	10
	Expansion ratio	1.2
Volume point	# volume point	3,781,486

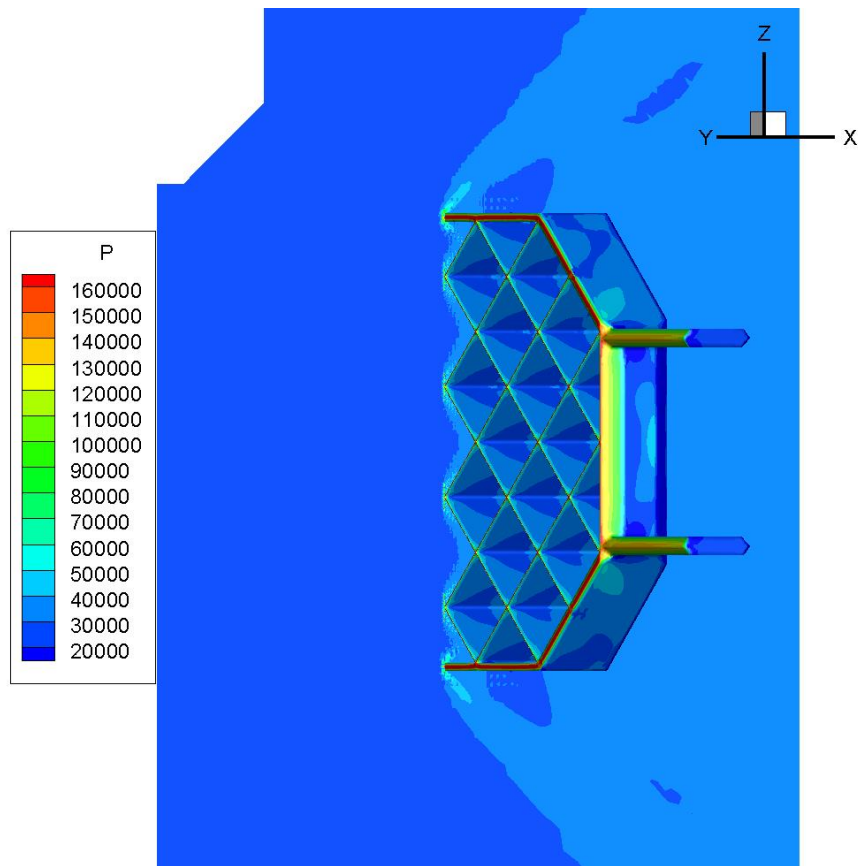


<Surface mesh>

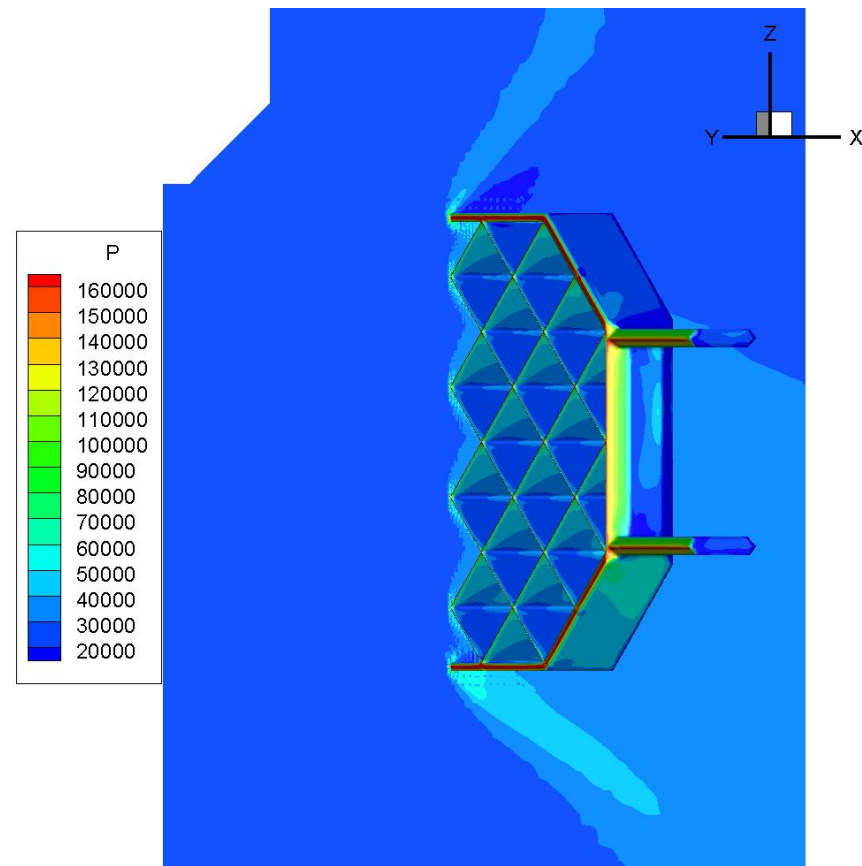


<Volume point system>

■ 압력 분포



<Pressure contour of fin and fin-center, AOA = 0>

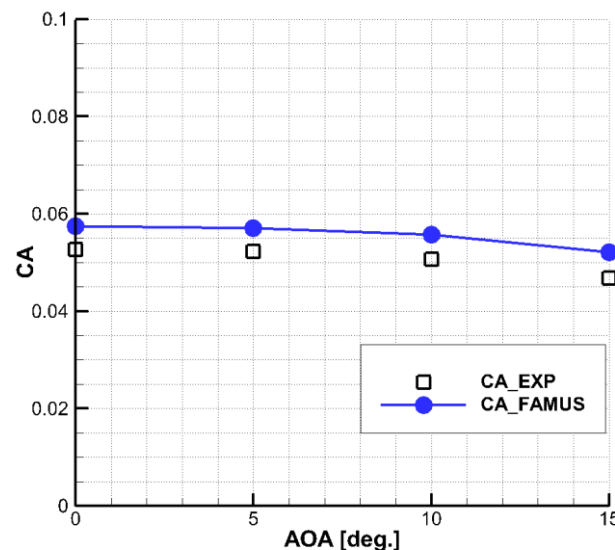
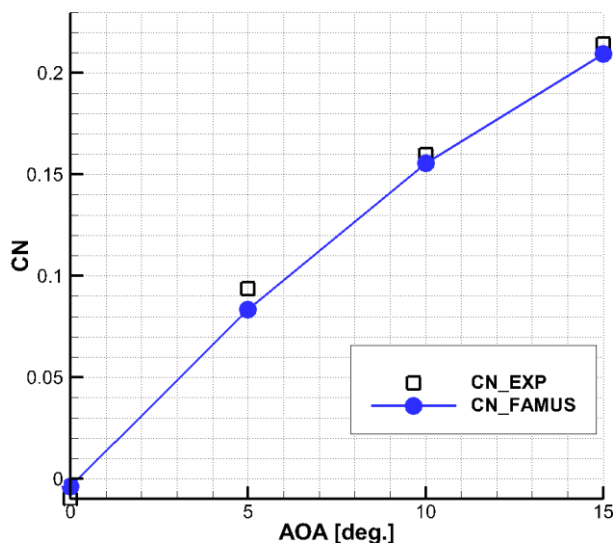


<Pressure contour of fin and fin-center, AOA = 10>

해석결과

■ 공력 계수

- Normal force : 실험값보다 작게 예측 (최대 11 % 차이 – AOA 5 도)
- Axial force : 실험값보다 10 % 가량 높게 예측
- 다른 CFD 연구와 비슷한 수준의 차이, Body effect 검토 필요



<Aerodynamic coefficient comparison>

<Normal force coefficient comparison>

CN				
AOA	0	5	10	15
Exp.	-0.0099	0.0938	0.1598	0.2143
FAMUS	-0.00374	0.08355 (-11 %)	0.1557 (-3 %)	0.2094 (-2 %)

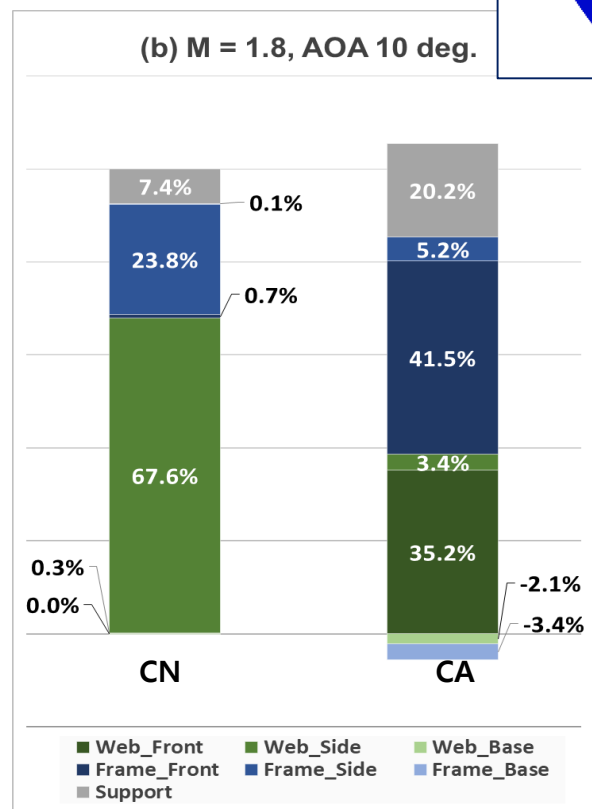
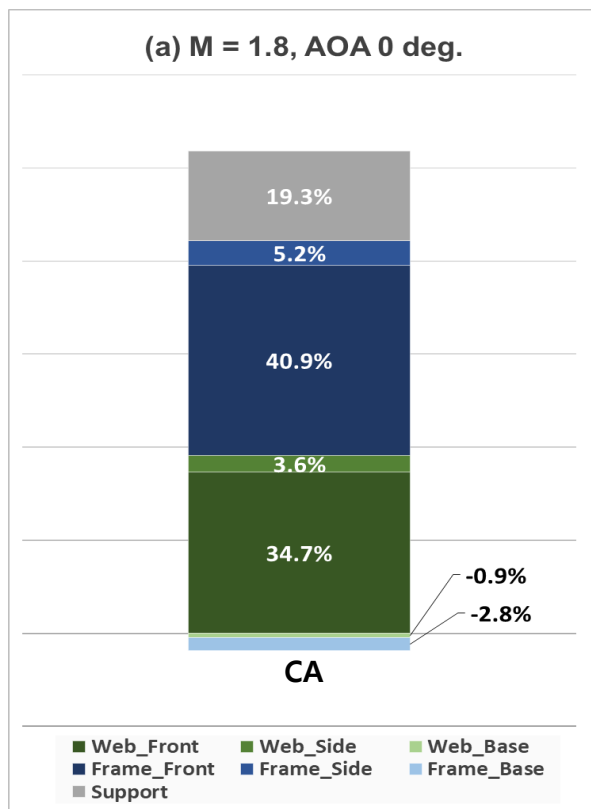
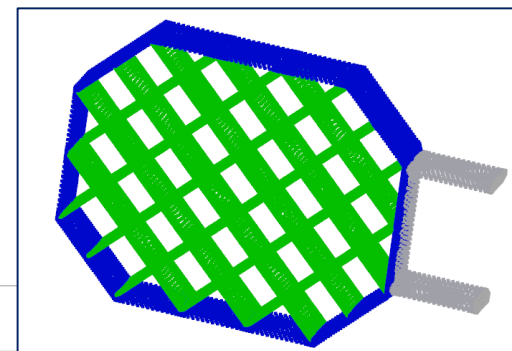
<Axial force coefficient comparison>

CA				
AOA	0	5	10	15
Exp.	0.0526	0.0523	0.0507	0.0468
FAMUS	0.05745 (9 %)	0.05705 (9 %)	0.05576 (10 %)	0.05211 (11 %)

■ 공력 계수

■ 그리드핀 sector 별 공력에 대한 기여

- Web / Frame / Support, Front / Side / Base
- Axial force : Web, Frame 각각 40, 45 % 기여
- Normal force : Web에서 약 70 % 기여



<Contribution of Grid-fin sectors to aerodynamic force>

IV. 결론

1. 요약
2. 후속 연구 내용

■ 요약

- 무격자 기반 유동해석 솔버(FAMUS)를 이용, 초음속 Benchmark 유동해석을 수행
- 실험값과 CFD 예측값 차이는 normal force 최대 -11 %, axial force 약 10 %
- 선행 CFD 연구 예측 결과와 유사한 수준의 차이

■ 후속 연구 내용

- Body-effect 분석
- 천음속, 아음속 Benchmark 테스트
- 그리드핀 형상 변수에 대한 민감도 분석

경청해 주셔서 감사합니다.

