2005 유체기계 연구개발 발표회 논문집, pp. 636~642
창원대학교 국제교류센터 및 정보전산원 2005. 12. 1~2

상용 유한요소 프로그램을 적용한 원자력 펌프의 구조해석

Structural Integrity Analysis on Horizontal Nuclear Power Pump

- 2005년 유체기계공업학회 유체기계 학술 대회 -

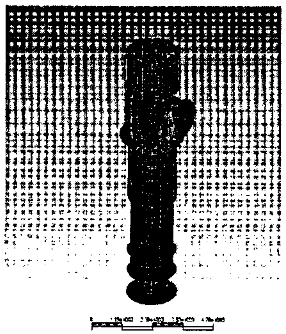
2005년12월1일(목)~ 12월2일(금)

서영수*, 정기철*, 박정석*, 정희택**

* 효성EBARA(주), Email: ysseo@hyosung.com
** 경상대학교 기계공학과

HYOSUNG EBARA CO., LTD. 1 / 24 R&D Institute Young Soo Seo

Contents



- INTRODUCTION
  - Background
  - Objectives
  - Previous Studies
  - Procedure of Analysis
  - Response Spectrum Analysis
  - Time History Analysis
- HORIZONTAL CENTRIFUGAL PUMP
  - Objectives
  - Design Specification
  - Material & Allowable Stress
  - 3D and Finite Element Model
  - Normal Mode Analysis
  - Nozzle Load and Service Limits
  - Stress Analysis
- CONCLUSION AND FUTURE STUDY

HYOSUNG EBARA CO., LTD. 2 / 24 R&D Institute Young Soo Seo

Background

- Dynamic and Environmental Qualification for Nuclear Power Plant Pumps
  - 원자력 발전소는 지진과 같은 가상적 사고(Postulated Accident)로 부터 안전성의 확보가 필수적임.
  - 원자력 안전등급 펌프는 구조적 건전성 및 운전 안전성을 입증하기 위한 엄격한 기기검증이 요구됨.
    - 능동기기(Active Equipment) : 구조적 건전성, 내압력 건전성 및 운전성의 입증
    - 수동기기(Passive Equipment) : 구조적 건전성, 내압력 건전성의 입증
  - Harsh Zone의 Class 1E의 전기 기기, 능동기기의 유기물과 같은 비금속 재료는 열화 및 노화(Aging)의 내환경 검증(Environmental Qualification)을 실시함.
- Seismic Qualification for Nuclear Power Pumps

Computer Analysis	Experimental Test	Test and Analysis
Static Analysis Dynamic Analysis	광대역 입의 운동시험 정현파 스위프 시험 지진 가상 모의실험	시험과 해석의 상호 보완 기수행 시험 기기의 동특성 분석

HYOSUNG EBARA CO., LTD. 3 / 24 R&D Institute Young Soo Seo

Objectives

- Preliminary Analysis
  - 고유진동수 해석을 통해 기기의 해석 방안을 결정
  - 진동 특성 파악을 위한 동적 거동을 시뮬레이션 해석

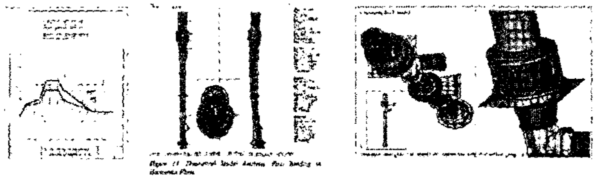
Static Analysis	Dynamic Analysis
강성(rigid)기기 계산 및 평가	유연성(flexible)기기 및 시간 이력해석
건전성 입증 노즐하중 및 지진하중	건전성 입증 노즐하중 및 지진하중
운전성 입증 해석 및 평가	운전성 입증 해석 및 평가

- 해석적 기법을 적용한 원자력 펌프의 동적 특성 파악
- 원자력 펌프의 구조적 건전성 확보 및 회전축계의 운전 안정성 입증

HYOSUNG EBARA CO., LTD. 4 / 24 R&D Institute Young Soo Seo

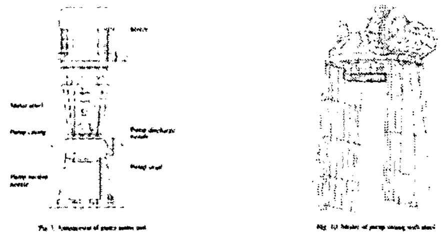
Previous Studies

- Karl Pottie, 2003, "Seismic Analysis on Modified Service Water Pumps", Proceedings of the twentieth international pump users symposium, Texas A&M University
  - ANSYS를 이용한 고유진동수 및 응력해석
  - 모달 측정 기법을 통한 고유 모드 및 진동수 측정
  - Essential Service Water Pump for Nuclear Power Plants in Spain

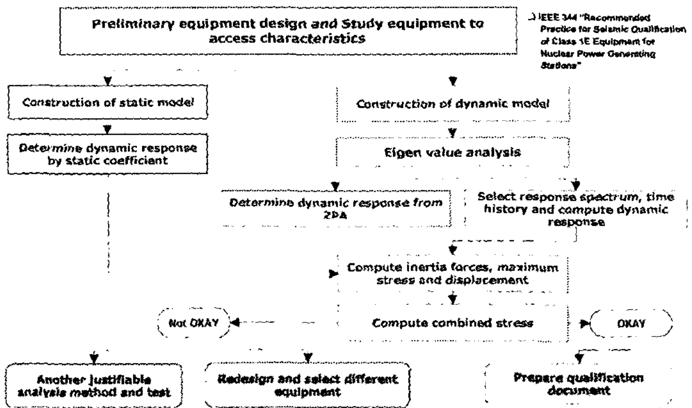


Previous Studies

- D.S. Chawla, R.S.Soni, H.S. Kushwaha, 1998, "Assessment of Operability and Structural Integrity of a Vertical Pump for Extreme Loads", International Journal of Pressure Vessels and Piping, pp. 297 - 306
- 석유화학용 프로세스 펌프를 원자력 발전소용 펌프에 적용하기 위해 펌프의 구조 건전성 및 운전성을 해석적으로 입증
  - 배관 노즐하중에 대한 펌프 케이싱의 응력 해석
  - 펌프계의 고유진동수 해석 및 공진 평가

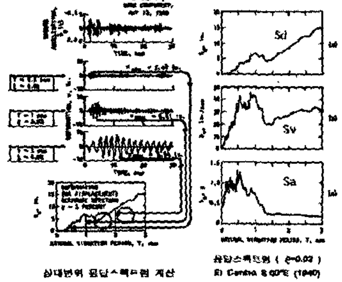


Procedure of Analysis



IEEE 344 "Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations"

Response Spectrum Analysis



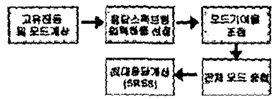
- 특정 지진에 대한 단자유도 시스템 구조물의 응답해석
- 고유진동수에 따른 구조물의 최대 응답을 산정
- 고유진동수 및 진동주기 변화에 따른 구조물 응답을 표현

$S_v = \omega S_d,\ S_a = \omega S_v = \omega^2 S_d$

S_d : Pseuo Displacement(유사변위)

S_v : Pseuo Velocity(유사속도)

S_a : Pseuo Acceleration(유사가속도)

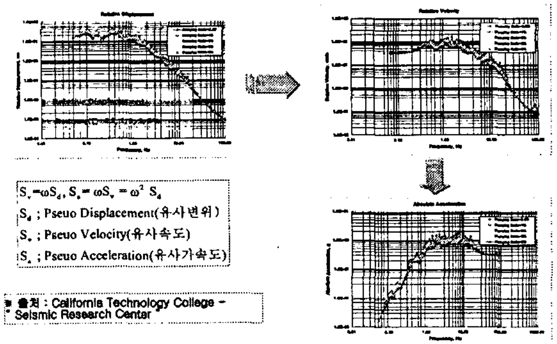


- SRSS (Square Root of the Sum of the Squares)

- 장 점
  - 구조물의 동적 특성을 고려함
  - 계산이 복잡하지 않으며, 설계용 스펙트럼으로 간편성
  - 구조물 응답의 최대치만을 구할 때 가장 효율적
- 단점
  - 시간에 따른 구조물 계의 동적 거동을 알 수 없음.
  - 비선형 해석 혹은 피로해석이 불가능함

Response Spectrum Analysis

❑ El Centro-IMPERIAL VALLEY EARTHQUAKE, 1940



$S_v = \omega S_d,\ S_a = \omega S_v = \omega^2 S_d$

S_d ; Pseuo Displacement(유사변위)

S_v ; Pseuo Velocity(유사속도)

S_a ; Pseuo Acceleration(유사가속도)

■ 출처 : California Technology College – Seismic Research Center

Time History Analysis

❑ Dynamic Equilibrium Equation for a multi-degree of freedom system

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F\}$$

❑ Dynamic Equilibrium Equation for a multi-degree of freedom system in case of earthquake ground acceleration

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=-[M]\{I\}\ddot{u}_g$$

$$\{u\}=[\Phi]\{q\},\{\dot{u}\}=[\Phi]\{\dot{q}\},\{\ddot{u}\}=[\Phi]\{\ddot{q}\}$$

$$[\Phi]^T[M][\Phi]\{\ddot{q}\}+[\Phi]^T[C][\Phi]\{\dot{q}\}+[\Phi]^T[K][\Phi]\{q\}=-[\Phi]^T[M]\{I\}\ddot{u}_g$$

비감쇠 고유진동수 해석 → 질량, 감쇠, 강성행렬의 ... → 모드별 단자유도 응답계산 → 각 모드 조합 전체응답계산 → 최대응답계산

$$m_i\ddot{q}_i+c_i\dot{q}_i+k_iq_i=Q_i$$;1개 상미분 방정식

$m_i=\{\phi\}_i^T[M]\{\phi\}_i,\ k_i=\{\phi\}_i^T[K]\{\phi\}_i,\ c_i=\{\phi\}_i^T[C]\{\phi\}_i$

$Q_i=\{\phi\}_i^T[M][I]\ddot{u}_g$

$$\ddot{q}_i+2\xi_i\omega_i\dot{q}_i+\omega_i^2q_i=Q_i/m_i=-\Gamma_i\ddot{u}_g(t)$$

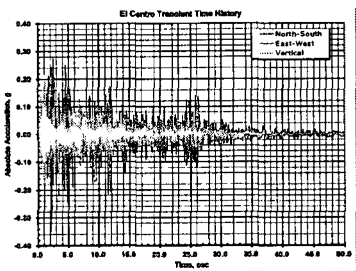
;일반화 비연성 운동방정식

■ 장점
- 각 모드의 단자유도계에 대한 독립적인 해석이 가능함
- 동적 거동을 지배하는 몇 개의 저차 진동 모드의 해석으로 아주 정확한 해를 얻을 수 있음.
- 직접 적분법에 비해 컴퓨터 계산시간을 절약할 수 있음

■ 단점
- 중첩의 원리를 적용하므로 선형 탄성해석에만 적용 가능함.

Time History Analysis

❑ 가속도 시간 이력 (1940년, El Centro- IMPERIAL VALLEY EARTHQUAKE)



DESCRIPTION	East-West, S90W	North-South, S00E	Vertical, VERT
No. of Points	1105	985	1324
Duration, sec	53.47	53.73	53.79
Peak Acceleration, cm/sec²	210.14	341.69	-206.35
Peak Velocity, cm/sec	-36.92	33.45	-10.84
Peak Displacement, cm	-19.78	10.87	-5.56

Objectives

❑ 기본 설계 ; 적용재질 및 구조결정 (설계 압력, 온도, 약품 및 유량 등)

❑ PRELIMINARY NORMAL MODE ANALYSIS를 통한 해석 방안 결정

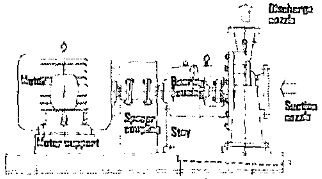
STRUCTURAL DESIGN CALCULATION
- 케이싱 최소 벽두께 계산
- 노즐 및 플랜지 응력 계산
- 케이싱 카버 및 볼트 응력 계산
- 기초 지지 볼트 응력 계산
- 베어링 수명 계산 등

STATIC ANALYSIS
- ...DIMENSIONAL AND FINITE ELEMENT MODELING
- 고유진동수 해석
- 특계 위험속도 해석
- 노즐 허용하중 및 반력
- 응력 및 지점 해석

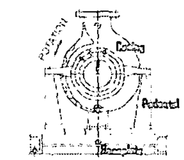
▶ 해석적 기법을 적용한 펌프의 동적 특성 파악

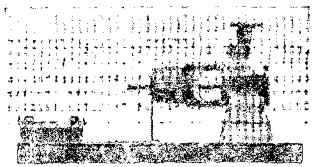
▶ 펌프의 구조적 건전성 확보 및 안전성 입증

Design Specification



Outline of component cooling water make-up pump



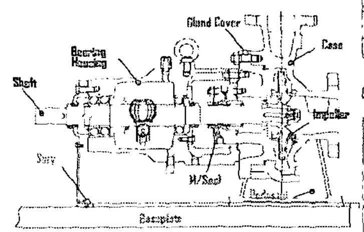


3-Dimensional model using Solid Edge/Ansys workbench

Quality class	Q
Design class	Safety class
Pump fluid	Condensate demi-water
Design pressure	1MPa
Design temperature	65℃
Capacity	41 m³/hr
Total head	43 m
NPSH required	2.5 m
BKP	11.6 hp
RPM	1760 ccw
Motor	20HP, TEFC, CLASS IE
Specific gravity	1.0

Material & Allowable Stress

- Equipment support : NF
- Pressure boundary : ND
- ASTM boundary



Sectional view of component cooling water make-up pump

❑ Pressure boundary parts(ND)

(unit:psi)

Component	Material	Yield Sy	Tensile Su	ND Allowable	ND Bend Allowable
Case	SA-351 Gr. CF3M	30,000	70,000	17,500	26,250
StudBolts, Case & Gland Cover	SA-193 B7	105,000		25,000	37,500
Gland Cover	SA-351 Gr. CF3M	30,000		17,500	26,250

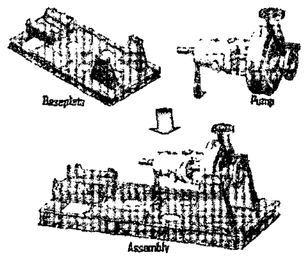
❑ Support boundary parts(NF)

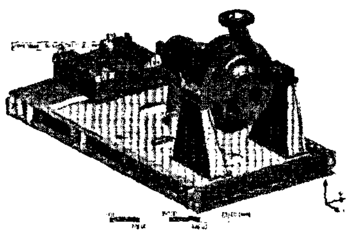
(unit:psi)

Component	Material	Condition	Yield Sy	Tensile Su	Allowable	NF Allowable
Bolts, Case pump	SA 193 B7	TENSILE	105,000	125,000	25,000	62,500
		SHEAR			12,500	25,833
Baseplate	SA 36	BEND	36,000	58,000		21,600
		SHEAR				14,400
Bolts for Stay fitting	SA 193 B7	TENSILE		125,000	25,000	62,500
		SHEAR			12,500	25,933
Motor hold Down bolt	SA 193 B7	TENSILE	105,000	125,000	25,000	62,500
		SHEAR			12,500	25,933

3 Dimensional Model

❑ 3 dimensional model(solid edge v. 16.0)

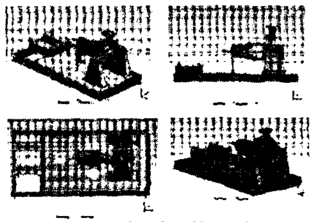




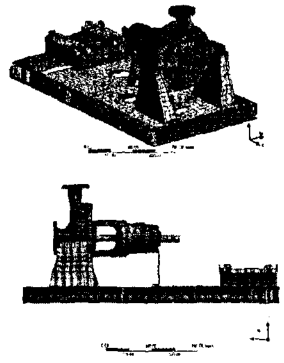
Component name	Weight
Pump	357 kg
Baseplate	363 kg
Total weight	720 kg

Finite Element Model

❑ Finite element model(ANSYS/WORKBENCH)



Nodes	202,428
Elements(Tetra 10)	96,317
Weight	722 kg



❑ Boundary condition

Anchor Bolts	Translation.	<0, 0, 0>
	Rotation	<0, 0, 0>

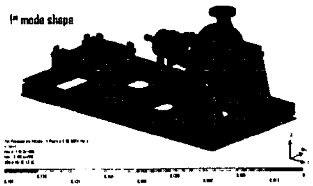
Normal Mode Analysis

Korean Fluid Machinery Association

❑ Natural Frequency (lanczos method)

Mode	Frequency(Hz)	Mode description
1st	58.89	shaft bending mode
2nd	59.23	shaft bending mode
3rd	81.9	case bending mode
4th	119.1	case torsion mode
5th	152.01	drain pan local mode
6th	163.5	drain pan local mode

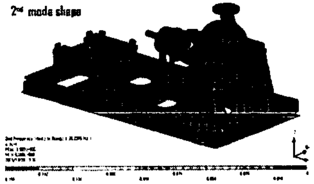
1st mode shape



❑ Participation Factor

Mode	Frequency	X direction	Y direction	Z direction
1st	58.89	-0.011	0.21	0.027
2nd	59.23	0.021	-0.0071	0.13
3rd	81.9	-0.021	-0.6	-0.12
4th	119.1	0.55	-0.058	0.22
5th	152.01	-0.24	-0.11	0.55
6th	163.5	-0.27	0.026	0.057

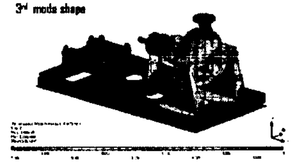
2nd mode shape



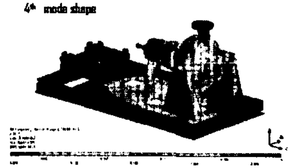
Normal Mode Analysis

Korean Fluid Machinery Association

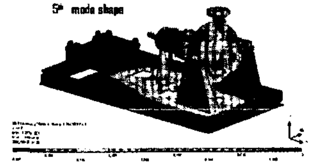
3rd mode shape



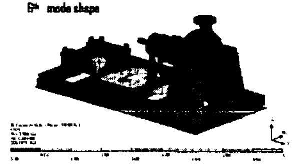
4th mode shape



5th mode shape



6th mode shape



Nozzle Load and Service limits

Korean Fluid Machinery Association

❑ Nozzle loads

Condition	Load	Suction(6")	Discharge(3")
Upset	Fr	25kN	10kN
	Mr	8kN-m	1.6kN-m
Upset	Fr	28kN	11kN
	Mr	8.8kN-m	1.8kN-m
Faulted	Fr	40kN	16kN
	Mr	15kN-m	3.1kN-m

❑ Dynamic load (2% damping)

OBE	Vertical	± 0.45g (dead weight : 1.0g)
	Horiztonal (both direction)	± 0.45g
SSE	Vertical	± 0.8g (dead weight : 1.0g)
	Horiztonal (both direction)	± 0.8g

* OBE(Operating Base Earthquake), SSE(Safe Shutdown Earthquake)

❑ Service limits and load

Service Limits	Pressure Design	Nozzle Load	OBE	SSE	σm	σm + σb
Design	●	●	N/A	N/A	S	1.5S
Level A	●	●	N/A	N/A	S	1.5S
Level B	●	●	●	N/A	1.1S	1.65S
Level D	●	●	N/A	●	2.0S	2.4S

Operating condition	Loading combination	Stress limits
Normal	Weight + Pressure + Thermal expansion + Equipt. operating loads	Service Limit A
Upset	Weight + Pressure + Thermal Expansion + Equipt. operating loads + Upset condition dynamics loads	Service Limit B
Emergency and Faulted	Weight + Pressure + Thermal Expansion + Equipt. operating loads + emergency / Faulted condition dynamic Loads	Service Limit D

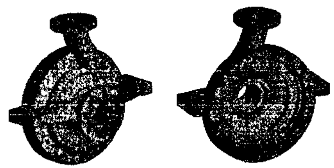
Stress Analysis – Design Pressure

Korean Fluid Machinery Association

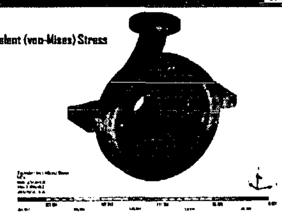
❑ Static Design Pressure (1MPa)

Minimum	Maximum	Description
23.7kPa	251.87 MPa	Local stress

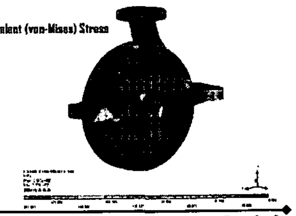
Nodes	95,560
Elements(Tetra 10)	58,785
Weight	131 kg



Equivalent (von-Mises) Stress



Equivalent (von-Mises) Stress



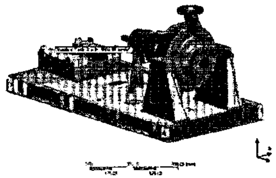
❑ Boundary condition

Pump Pedestal	Translation, Rotation	< 0, 0, 0 > < 0, 0, 0 >

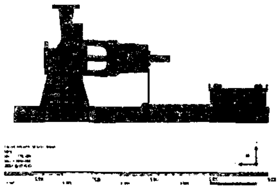
Stress Analysis – ...ead Weight

❑ Dead weight (1g)

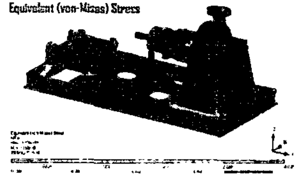
Minimum	Maximum	Description
-	11.29 MPa	Foundation Bolt



Equivalent (von-Mises) Stress



Equivalent (von-Mises) Stress



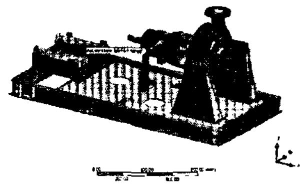
❑ Boundary condition

Anchor Bolt	Translation, Rotation	<0, 0, 0> <0, 0, 0>

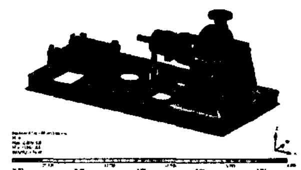
Stress Analysis – ...ynamic Load

❑ Dynamic load (latitude, longitude 1g)

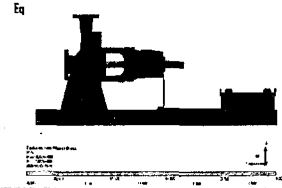
Minimum	Maximum	Description
-	26.1 MPa	Foundation Bolt



Equivalent (von-Mises) Stress



Eq



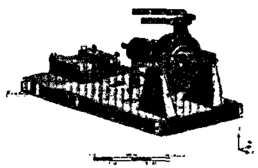
❑ Boundary condition

Anchor Bolt	Translation, Rotation	<0, 0, 0> <0, 0, 0>

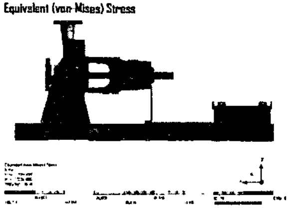
Stress Analysis – ...ozzle Load

❑ Nozzle Loads (forces, moments)

Minimum	Maximum	Description
-	190.2 MPa	Foundation Bolt



Equivalent (von-Mises) Stress



Equivalent (von-Mises) Stress

❑ Boundary condition

Anchor Bolt	Translation, Rotation	<0, 0, 0> <0, 0, 0>

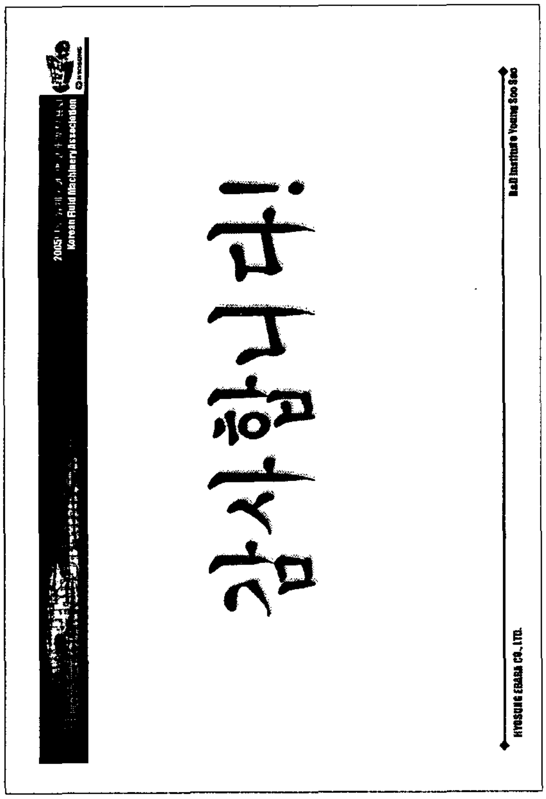
Conclusion... Future Study

❑ Conclusion

- 기본 설계 단계에서 수평형 원자력 펌프의 구조해석 기법을 적용하기 위한 절차를 제시함.
- 고유진동수 해석을 통해 수평형 원자력 펌프의 정적 해석 기법의 적용 타당성을 입증함.
- 흡입, 토출 노즐에 작용하는 노즐 하중과 동적(내진)하중을 고려한 구조 응력 해석을 실시하여 재질의 허용응력 관점에서 평가함.

❑ Future Study

- 해석 결과의 신뢰도 향상 및 검증을 위해 향후에 고유 진동수의 측정등과 같은 실험적 기법의 도입 예정임.
- 일반적으로 고유진동수가 낮은(33Hz이하) 수직형 원자력 펌프의 동적해석 기법의 적용 사례와 해석 절차를 발표 예정임.



Korean Fluid Machinery Association
감사합니다!
HYOSUNG EBARA CO., LTD.
R&D Institute Young Soo Seo