Application of Noise and Vibration Technology to Development of Vehicle Engineering

應用振動與噪音技術於車輛工程之發展

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- Position:
  - NPUST
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    - President (2014~2016)
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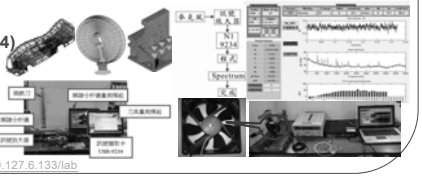
  - Dean, Eng. College (2007-2010)
  - Chief Secretary (2003-2005)
  - Director, Extension Education (2001)
  - Char, Dept. of ME (1997-2000)
  - Chief, RD Division(1994-1997)
  - Chief, Machinery Lab (1991-1994)
- Specialization
  - Vibration & Acoustics
  - CAE/FEA & EMA
  - Vehicle Dynamics
  - Musical Instruments

- Research Interest
  - Integration of CAE/EMA for VT

- Customized N&V Measurement System



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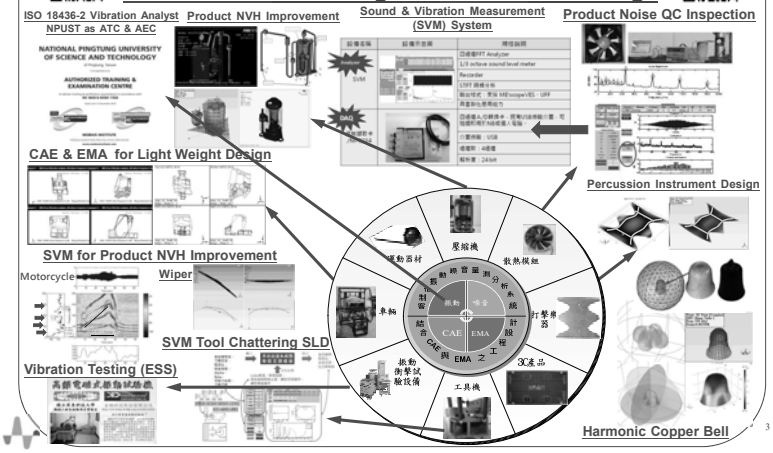
AITA/NVH Core Techniques

Fundamental knowledge ➔ Domain knowledge



Keyword Analysis

- 應用 Application of
  - application technique, practical consideration
- 振動與噪音 Noise and Vibration
  - NVH, noise/vibration/harshness
- 技術 Techniques
  - what techniques?
    - Analysis & Testing, control, prevention, etc.
      - 振動與噪音技術 Noise and Vibration Techniques
        - what is the total solution strategy?
- 車輛工程 to Vehicle Engineering
  - Vehicle engineering, “vehicle”?
- 發展 Development
  - development trend, need, future work

Outline

1. Introduction

- Noise, vibration and harshness (NVH) is of importance in vehicle engineering.
  - Noise and vibration (N&V) may also be a short and concise term for dealing vehicle design and related to ride comfort and ride quality.
- Other than the noise emission affecting the passengers inside of vehicle,
  - the noise radiation from vehicles also contributes to environmental noise.
  - Study shows the transportation noise may increase the cardiovascular risk [1].

1. Introduction

- COST (European Cooperation in Science and Technology) initiated Action TU1105 in 2012
  - to engage NVH experts in the accumulation, development and dissemination of novel techniques
    - for the analysis, design and optimization of hybrid and electric vehicle.
  - The progressive report “NVH analysis techniques for design and optimization of hybrid and electric vehicles” [2] was documented in 2016.
  - This attempt is to deal with common NVH issue
    - not only for consumer comfort and safety concern
    - but also for ecologic and economic constraints.
- COST Action TU1105 can inspire us to examine vehicle’s NVH in a highly global aspect.

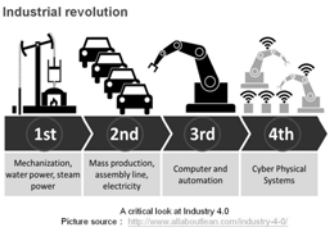
http://www.cost.eu/

1. Introduction

- “Industry 4.0” is drawn much attention recently.
- Wang [7] indicated that the spirits of Industry 4.0 can be
  - “Feedback” for Internet of Things (IoT) and
  - “Solution” for Cyber-Physical System (CPS).
- Although the development and implement of Industry 4.0 may dedicate to any product design and manufacture,
  - the involved NVH issues can also be carried out under the spirits of Industry 4.0.
- This work will
  - briefly review the content of Industry 4.0 and
  - link to NVH techniques development.

2. What is "Industry 4.0"?

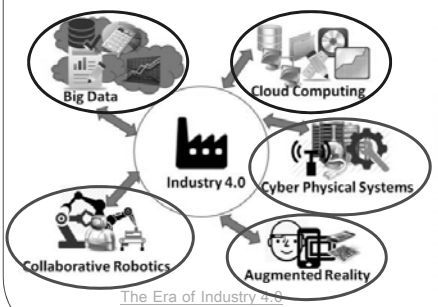
- Germany
  - Industry 4.0
- United State of America
  - Advanced Manufacturing Partnership (AMP)
- Japan
  - Society 5.0
- China
  - Made in China 2025
- Korea
  - Industry Innovation 3.0
- Taiwan
  - Productivity 4.0



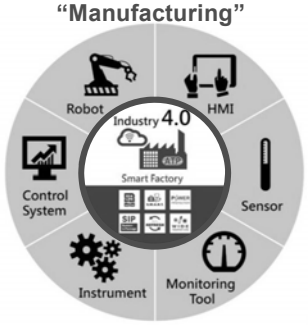
Two Issues in Industry 4.0

(1) Internet of Things (IoT)
(2)Cyber-Physical Systems (CPS)

From the point of view for
"Design"
"Manufacturing"



The Era of Industry 4.0
圖片來源：http://rvantage.net/internet-of-things-smart-manufacturing-the-era-of-industry4-0/



Automation Industry: Industry 4.0
圖片來源：http://embedded-computing.com/white-papers/white-0-challenges-solutions-storage-devices/

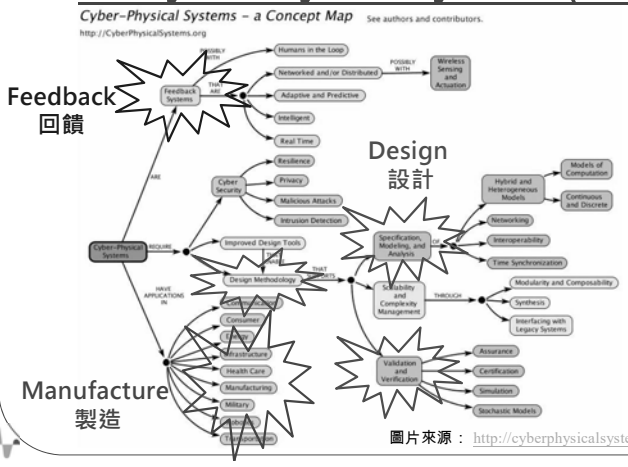
2.1-Internet of Things (IoT)

物聯網(Internet of Things, IoT)
圖片來源：http://www.allaboutlean.com/industry-4-0/internet-of-things/

2.2-Cyber-Physical Systems (CPS)

- Cyber
  - 網絡：
    - of, relating to, or characteristic of the culture of computers, information technology, and virtual reality.
  - 聯網、網際：
    - relating to electronic communication networks and virtual reality
- Physical Systems
  - Software: to analyze …
  - Hardware: to measure …
- Cyber-Physical Systems
  - 網宇實體系統
  - 資訊物理系統
  - 虛實整合系統 ➔ This is what I prefer!
  - 訊息物理(融合)系統
  - 智慧整合感控系統

2.2-Cyber-Physical Systems (CPS)

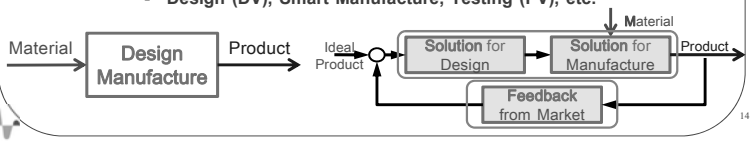


圖片來源： http://cyberphysicalsystems.org/

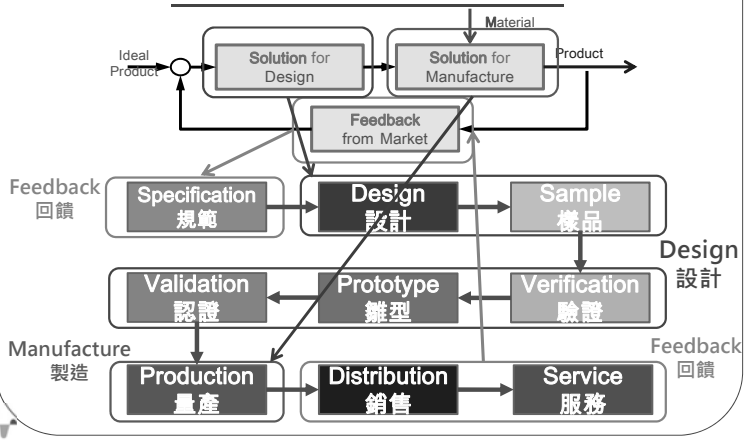
My Perspectives of Two Keywords for Spirits of Industry 4.0

(1) Feedback：
- Ability to collect the product information during design, manufacture, transportation, market, etc.
  - Information about reactions to a product, a person's performance of a task, etc., used as a basis for improvement.
    - Big data, IoT, Cloud, wireless sensor, smart sensing, etc.

(2) Solution：
- Ability to solve for the feedback problems and customer's concerns
  - A means of solving a problem or dealing with a difficult situation.
    - Design (DV), Smart Manufacture, Testing (PV), etc.

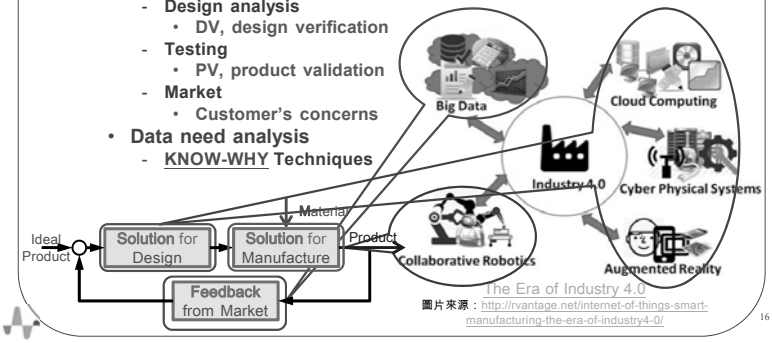


Product Development Process with Feedback and Solution



My Perspectives of Two Keywords for Spirits of Industry 4.0

(1) IoT ➔ Feedback
- Data ➔ Information
  - Data may come from ➔ KNOW-WHAT Techniques
    - Design analysis
      - DV, design verification
    - Testing
      - PV, product validation
    - Market
      - Customer's concerns
  - Data need analysis
    - KNOW-WHY Techniques

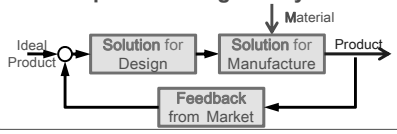


The Era of Industry 4.0
圖片來源：http://rvantage.net/internet-of-things-smart-manufacturing-the-era-of-industry4-0/

My Perspectives of Two Keywords for Spirits of Industry 4.0

(2) CPS → Solution → KNOW-HOW Techniques

- Testing → Virtual Testing
  - Product Testing → Product Validation (PV)
  - Virtual Testing (VT) → CAE Application
    - Model Verification (MV) → Design Modification (DM)
- CAE → Experimental Verification
  - Design Analysis → Design Verification (DV)
  - Experimental techniques → CAT
- Verification → Validation (V&V)
  - DV 設計驗證(design verification)
  - PV 產品認證(product validation)
- Component design → System design

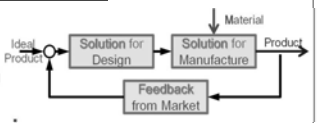


Crotale with Harmonic Sound

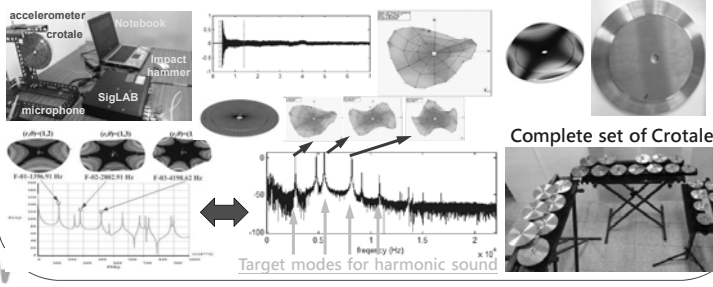
Design and Development of Crotale with Harmonic Sound
具簡諧倍頻音古鈸打擊樂器之設計開發

(2) CPS → Solution

- Testing → Virtual Testing
- CAE → Experimental Verification
- Verification → Validation
- Component design → System design



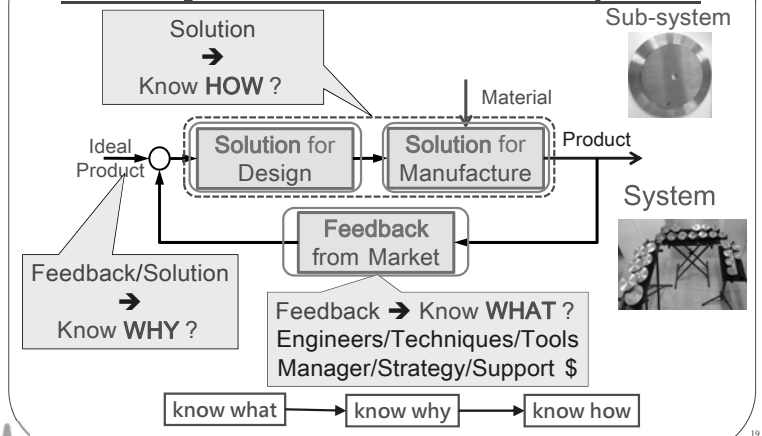
Single crotale



Complete set of Crotales

Target modes for harmonic sound

Industry 4.0 for Product Development

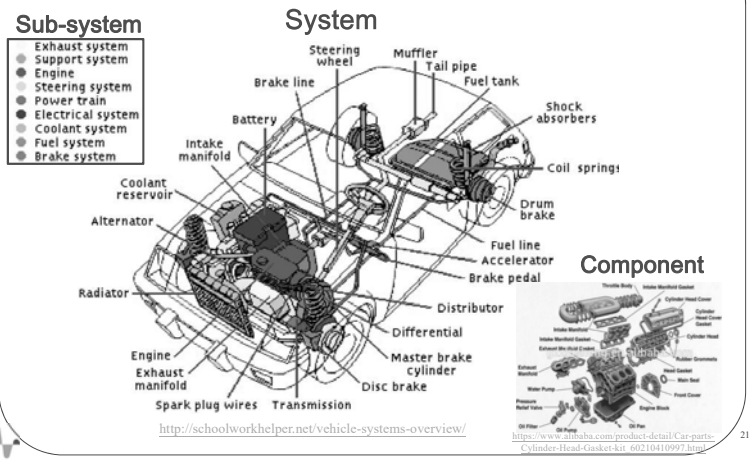


Six stages of "Engineering design" ?

- Functional design
- Safety design
- Performance design
- Quality design
- Reliability design
- Brand design – system engineering
  - Design for manufacturing
  - Design for assembly
  - Design for low noise & vibration
  - Design for reliability
    - Design for ???

- Federal Motor Vehicle **Safety** Standards (**FMVSS**) [10],
  - the U.S. federal regulations specifying **design**, **construction**, **performance**, and **durability** requirement for motor vehicle, can be a good example in discussing vehicle design regarding the six stages.
- NVH related techniques are crucial to each stage of design.

Concept of "System→ Sub-system → Component"



http://schoolworkhelper.net/vehicle-systems-overview/

https://www.alibaba.com/product-detail/Car-parts-Cylinder-Head-Gasket-kit_60210410997.html

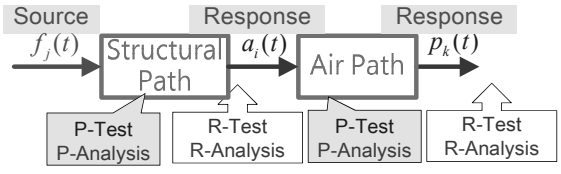
Outline

- 1. Introduction
- 2. Spirits of Industry 4.0
- 3. Fundamental Knowledge of Sound and Vibration
  - 3.1 System Block Diagrams for ISO and SPR
  - 3.2 Vibration and Dynamics
  - 3.3 Acoustics: Sound/Noise
  - 3.4 System – Sub-system – Component
- 4. General Approach
  - in Product Development and Improvement
- 5. NVH Diagnosis Approach
- 6. Conclusions and Recommendations

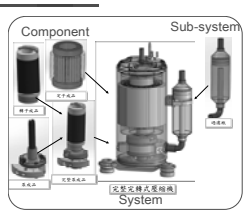
3.1 System Block Diagrams for ISO and SPR

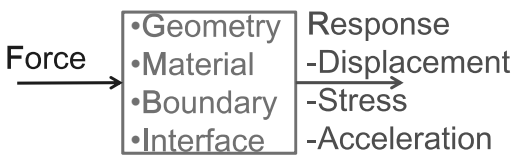
- **ISO**
  - Input → System → Output

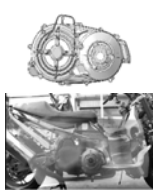
- **SPR**
  - Source → Path → Receiver/Response
    - Structural Path
    - Air Path



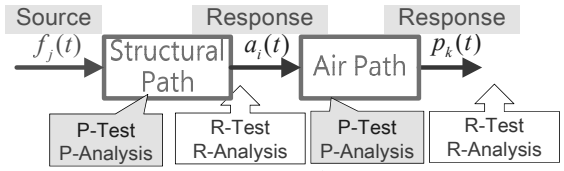
System Concept
ISO – SPR – F→GMBI→R



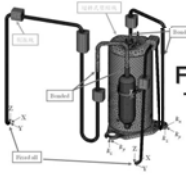




From "Component" to "System"



Component

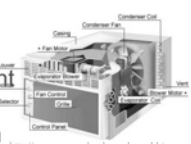


Force

- Geometry
- Material
- Boundary
- Interface

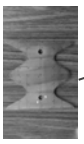
Response
-Displacement
-Stress
-Acceleration

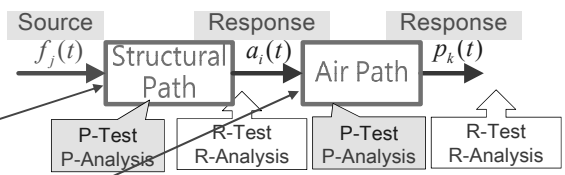
System

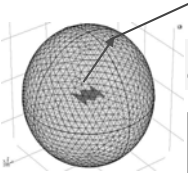


http://www.energyland.emsd.gov.hk/en_building/district_cooling_sys/conventional.html

SPR & ISO Concept







輸入 (Input) → 系統 (System) → 輸出 (Output)

振動源 (Source) → 路徑 (Path) → 收受端 (Receiver)

- ISO
- SPR

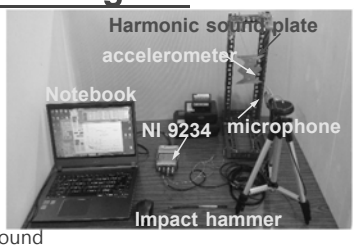
SYSTEM analysis (P-Test)

SIGNAL analysis (R-Test)

- Path Test → SYSTEM analysis
  - To identify system "contents"
    - Modal parameters
    - FRF
- Receiver Test → SIGNAL analysis
  - To measure response only
  - To characterize the response for further applications

System Block Diagram

Force → 1.Geometry 2.Material 3.Boundary → Deformation Stress Acceleration



P-Test/P-Analysis (structure system)

Striking force → Structural Path → Structural Vibration → Air Path → Sound Pressure → Ear → Feelings → Brain

$f_j(t)$ → $H_{a_i,f_j}(f)$ → $a_i(t)$ → $H_{p_k,a_i}(f)$ → $p_k(t)$

P-Test/P-Analysis (air-structure system)

$f_j(t)$ → $H_{p_k,f_j}(f) = H_{a_i,f_j}(f) H_{p_k,a_i}(f)$ → $p_k(t)$

R-Test/R-Analysis

System block diagram for Structure-only System

Time domain: $f_j(t)$ → $[M_s][C_s][K_s]$ → $a_i(t)$

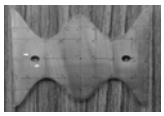
Frequency domain: $G_{f_jf_j}(f)$ → $H_{a_i,f_j}(f)$ → $G_{a_ia_i}(f)$

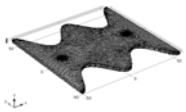
Modal domain: $f_j(t)$ → $f_r \to \phi_r \to \zeta_r$ → $a_i(t)$

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{f\}$$

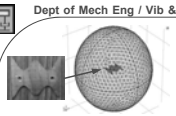
$$H_{ij}(\omega)=\frac{X_i}{F_j}=\sum_{r=1}^{n}\frac{\phi_{r,i}\phi_{r,j}}{(\omega_r^2-\omega^2)+i(2\zeta_r\omega_r\omega)}$$

$$H_{a_i,f_j}(\omega)=\frac{A_i}{F_j}=-\omega^2\sum_{r=1}^{n}\frac{\phi_{r,i}\phi_{r,j}}{(\omega_r^2-\omega^2)+i(2\zeta_r\omega_r\omega)}$$

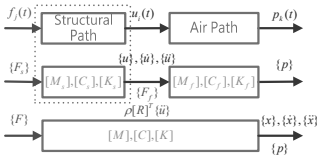




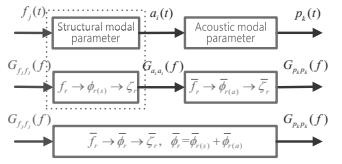
System block diagram for air-structure analysis



(a) Physical domain



(b) Modal domain



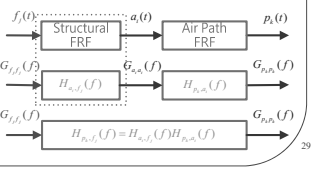
$$[M_s]\{\ddot{u}\}+[C_s]\{\dot{u}\}+[K_s]\{u\}=\{F_s\}+[R]\{p\}$$

$$[M_f]\{\ddot{p}\}+[C_f]\{\dot{p}\}+[K_f]\{p\}=\{F_f\}-\rho_0[R]^T\{\ddot{u}\}$$

$$\begin{bmatrix}[M_s] & 0\\ \rho_0[R]^T & [M_f]\end{bmatrix}\begin{Bmatrix}\{\ddot{u}\}\\ \{\ddot{p}\}\end{Bmatrix}+\begin{bmatrix}[C_s] & 0\\ 0 & [C_f]\end{bmatrix}\begin{Bmatrix}\{\dot{u}\}\\ \{\dot{p}\}\end{Bmatrix}+\begin{bmatrix}[K_s] & -[R]\\ 0 & [K_f]\end{bmatrix}\begin{Bmatrix}\{u\}\\ \{p\}\end{Bmatrix}=\begin{Bmatrix}\{F_s\}\\ \{F_f\}\end{Bmatrix}$$

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

(c) Frequency domain

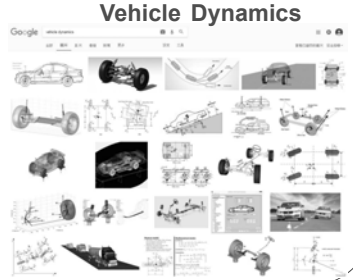


3.2 Vibration and Dynamics

- **Difference between "Vibration" and "Dynamics"?**
  - **Vibration: microscopic**
    - **Ride quality/ride comfort, fatigue analysis, etc.**
  - **Dynamics: macroscopic**
    - **Accelerated, braking, handling, etc.**

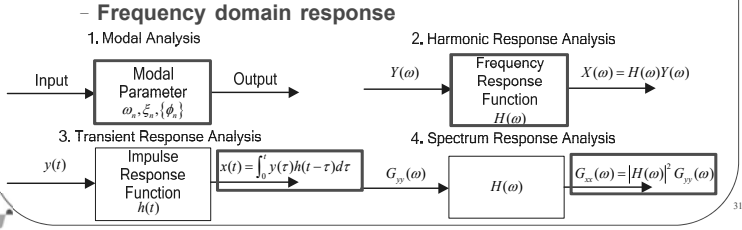
Vehicle Vibration

Vehicle Dynamics

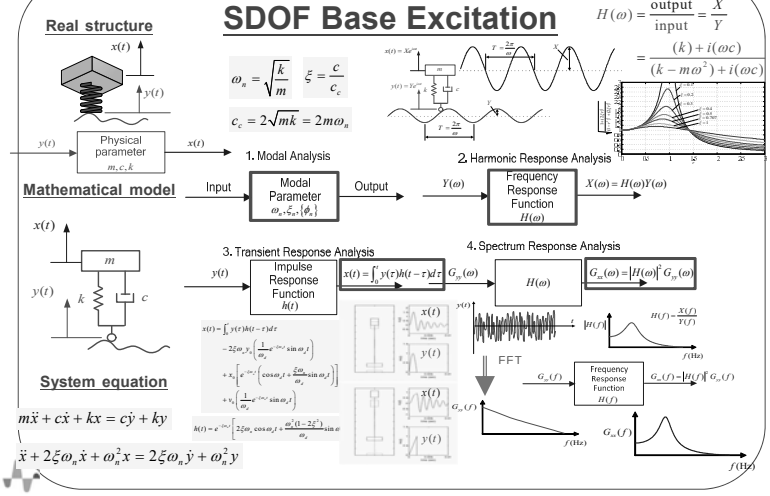


Four Types of Vibration Analysis

- **Modal Analysis (MA)**
  - **Modal parameters**
- **Harmonic Response Analysis (HRA)**
  - **FRF & ODS**
- **Transient Response Analysis (TRA)**
  - **Time domain response**
- **Spectrum Response Analysis (SRA)**
  - **Frequency domain response**

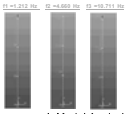


SDOF Base Excitation

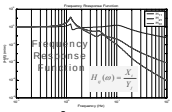


3-DOF Quarter Car Model

Real structure

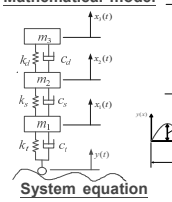


1. Modal Analysis



2. Harmonic Response Analysis

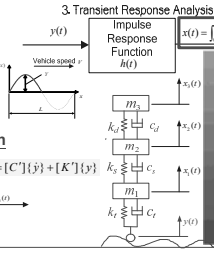
Mathematical model



Input → Modal Parameter $\omega_n, \xi_n, \{\phi_n\}$ → Output

$Y(\omega)$ → Frequency Response Function $H(\omega)$ → $X(\omega) = H(\omega)Y(\omega)$

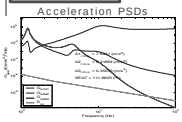
3. Transient Response Analysis



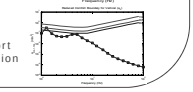
$x(t) = \int_0^t y(\tau)h(t-\tau)d\tau$

4. Spectrum Response Analysis

$G_{xx}(\omega)$ → $H(\omega)$ → $G_{yy}(\omega) = |H(\omega)|^2 G_{xx}(\omega)$



FFT

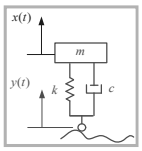


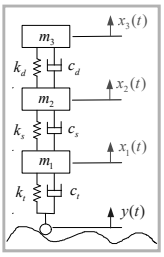
System equation

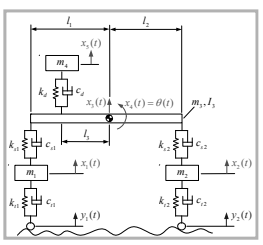
$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=[C']\{\dot{y}\}+[K']\{y\}$$

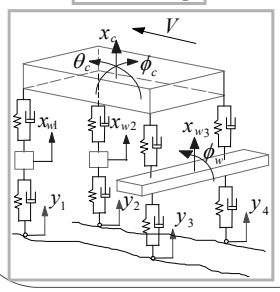
Ride Comfort Evaluation

Mathematical Model for Car









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3.3 Acoustics: sound/noise

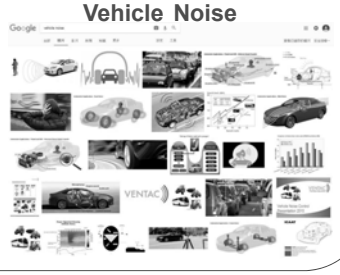
- What difference between Sound & Noise?
  - Unwanted
  - Undesired
  - Disturbance
  - Annoyance

Noise Control (噪音控制)

Sound Management (樂/悅音管理)

Vehicle Sound

Vehicle Noise

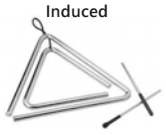


聲 (sound)

- Flow and Body interaction
  - 聲者，形氣相軋而成。
    - Flow - Flow：兩氣者，谷響雷聲之類。
      - Flow induced sound
    - Body - Body：兩形者，桴鼓叩擊之類。
      - Structural vibration induced sound
    - Body - Flow：形軋氣，羽扇敲矢之類。
      - Vibro-acoustic coupling sound
    - Flow - Body：氣軋形，人聲笙簧之類。
      - Fluid-Structural interactive coupling sound

兩氣者 Flow Induced

兩形者 Structural Vibration Induced



形軋氣 Vibro-Acoustic Coupling

氣軋形 Flow-Structure Interactive Coupling

What "index" for sound/noise evaluation ?

Function → Sensor → Measurement → **Index** → Criterion → Improvement

Sound Pressure Level (SPL)

$$L_P = 20\log\left(\frac{p}{p_{ref}}\right) \quad \text{dB } re\ 20\times10^{-6}\ \text{Pa}$$

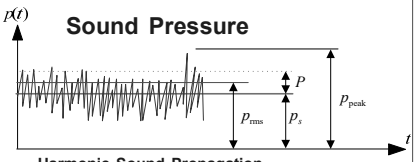
Sound Intensity Level (SIL)

$$L_I = 10\log\left(\frac{I}{I_{ref}}\right) \quad \text{dB } re\ 10^{-12}\ \text{W/m}^2$$

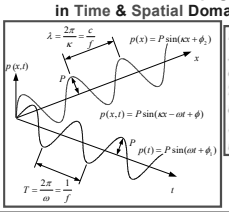
Sound Power Level (SWL)

$$L_W = 10\log\left(\frac{W}{W_{ref}}\right) \quad \text{dB } re\ 10^{-12}\ \text{W}$$

Sound Pressure

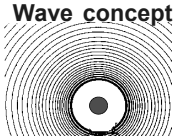


Harmonic Sound Propagation in Time & Spatial Domains



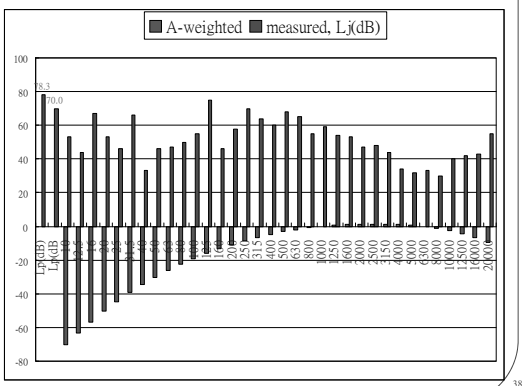
P: amplitude (Pa)
f: frequency (Hz)
ω: circular frequency (rad/s)
T: period (s)
c: sound speed (m/s)
λ: wave length (m)
κ: wave number (1/m)

Wave concept



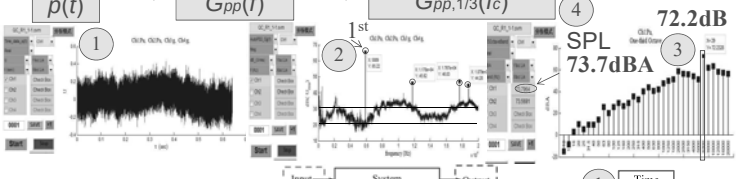
SPL in 1/1 or 1/3 Octave Band dB or dB(A)

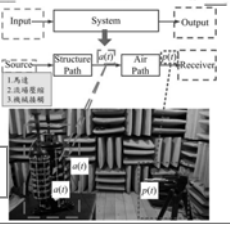
frequency	A-weighted	measured, Lj(dB)
Lp(dB)		78.3
Lp(dBA)		70.0
10	-70.4	53
12.5	-63.4	44
16	-56.7	67
20	-50.5	53
25	-44.7	46
31.5	-39.4	66
40	-34.6	33
50	-30.2	46
63	-26.2	47
80	-22.5	50
100	-19.1	55
125	-16.1	75
160	-13.4	46
200	-10.9	58
250	-8.6	70
315	-6.6	64
400	-4.8	60
500	-3.2	68
630	-1.9	65
800	-0.8	55
1000	0	59
1250	0.6	54
1600	1	53
2000	1.2	47
2500	1.3	48
3150	1.2	44
4000	1	34
5000	0.5	32
6300	-0.1	33
8000	-1.1	30
10000	-2.5	40
12500	-4.3	42
16000	-6.6	43
20000	-9.3	55



What are the interested "output response" ?
【R-Test】for Sound ?

Time $p(t)$ → Spectrum $G_{pp}(f)$ → 1/3 octave band $G_{pp,1/3}(f_c)$ → dB/dBA





振動/音源 (Source) → 路徑 (Path) → 收受端 (Receiver)

System Analysis (P-Test)

Signal Analysis (R-Test)

1 Time domain

2 噪音$p(t)$ 振動$a(t)$ → Linear PSD

3 量測程序 → 1/3 Octave band

4 dB/dBA → 噪音$p(t)$ 振動$a(t)$

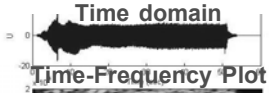
分析流程

What are the interested "output response" ?
【R-Test】for Sound ?

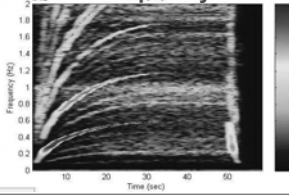
Time $p(t)$ → Spectrum $G_{pp}(f)$ → 1/3 octave band $G_{pp,1/3}(f_c)$ → dB/dBA

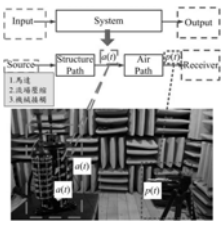
$p(t)$ → FFT → $P(f)$ → $P^*(f)P(f)$ → $G_{pp}(f)$ → $\sum_{f=f_L}^{f_U} G_{pp}(f)$ → $G_{pp,1/3}(f_c)$ → $\sum G_{pp,1/3}(f_c)$ → dB

Time domain



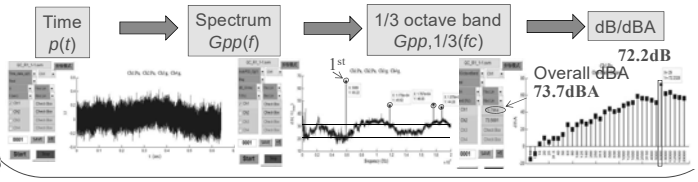
Time-Frequency Plot





Some Terminology for Measurement Quantity

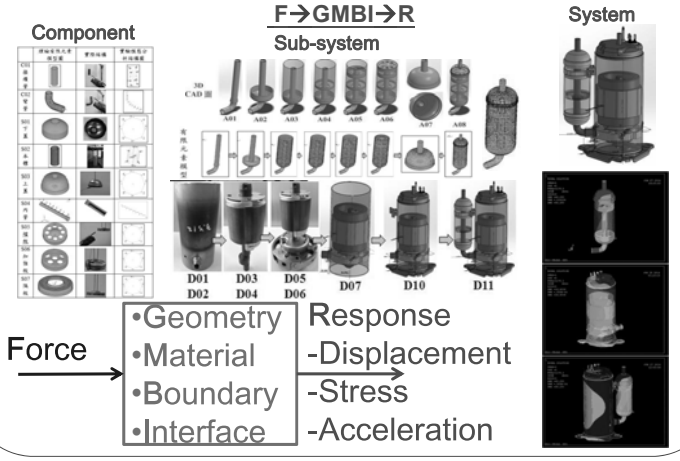
- $p(t)$: time domain response
- $G_{pp}(f)$: auto spectrum, auto PSD, power spectral density function
- $G_{pp,1/3}(f_c)$: one third octave band spectrum
- dB/dBA : sound pressure level (SPL) decibel / A weighted SPL
  - Noise → sound pressure, $p(t)$ (Pa)
  - Vibration → acceleration, $a(t)$ (m/s²), (g), 1(g)=9.807 (m/s²)
    - Also for Force (N)/Displacement (m)/Velocity (m/s)
      - $f(t)$ / $x(t)$ / $v(t)$



3.4 System – Sub-system – Component

System Modeling: Component → Sub-System → System

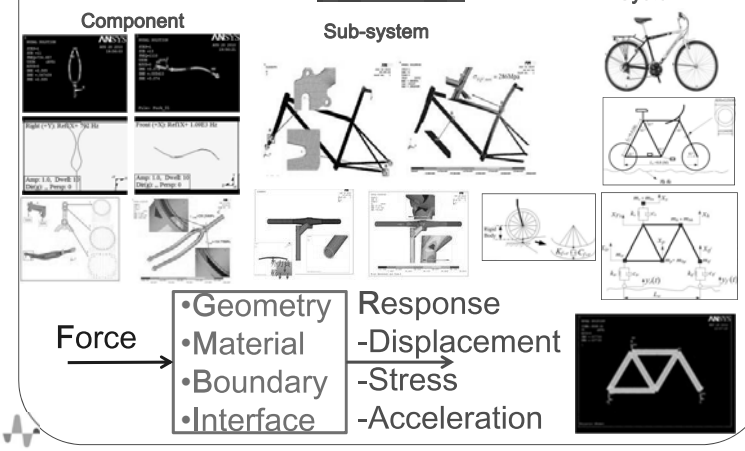
F→GMBI→R



Force → •Geometry •Material •Boundary •Interface → Response -Displacement -Stress -Acceleration

System Modeling: Component → Sub-System → System

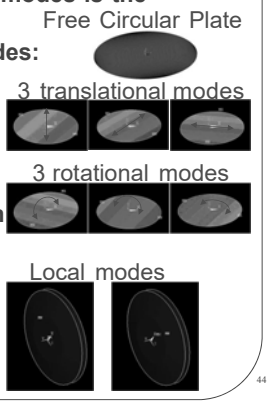
F→GMBI→R



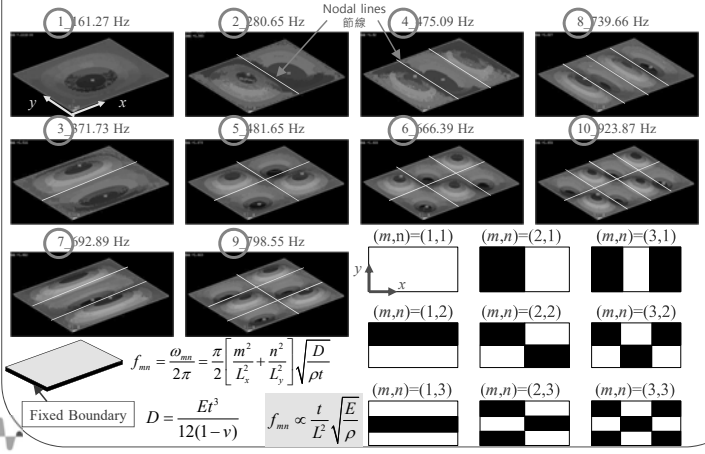
Force → •Geometry •Material •Boundary •Interface → Response -Displacement -Stress -Acceleration

Interpretation of Structural Vibration Modes

- Interpretation of structural vibration modes is the essential skill to NVH problems.
- There are two types of vibration modes:
  - rigid body modes
  - flexible body modes
- For rigid body modes, there are
  - three translational modes
  - three rotational modes
- The flexible body modes can contain
  - global modes
  - local modes



Typical Plate Mode Shape $(x,y)=(m,n)$



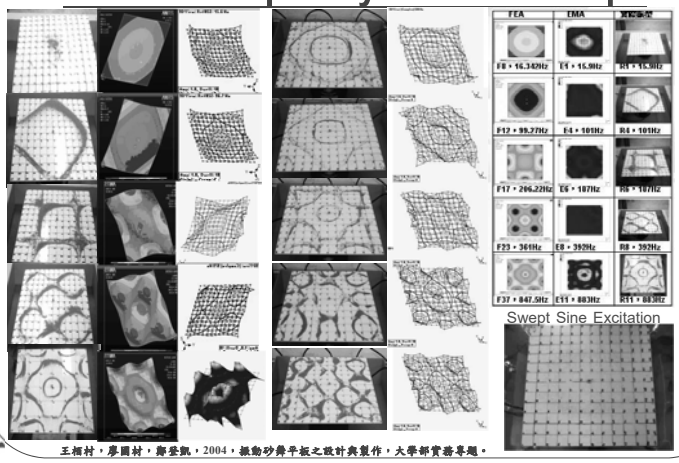
$$f_{mn} = \frac{\omega_{mn}}{2\pi} = \frac{\pi}{2}\left[\frac{m^2}{L_x^2} + \frac{n^2}{L_y^2}\right]\sqrt{\frac{D}{\rho t}}$$

Fixed Boundary

$$D = \frac{Et^3}{12(1-v)}$$

$$f_{mn} \propto \frac{t}{L^2}\sqrt{\frac{E}{\rho}}$$

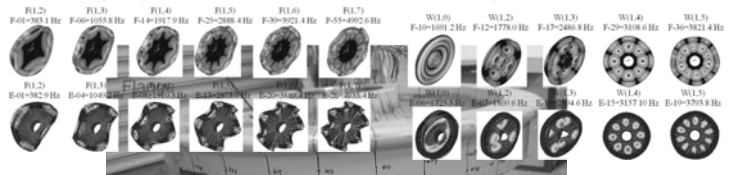
Natural Frequency → Mode Shape



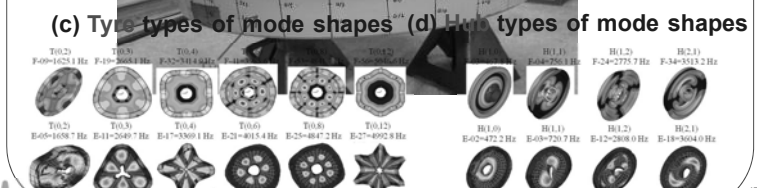
王相村，摩國村，鄭榮凱，2004，振動砂舞平板之設計與製作，大學部實務專題。

Vibration Modes for Steel Wheel in free boundary condition

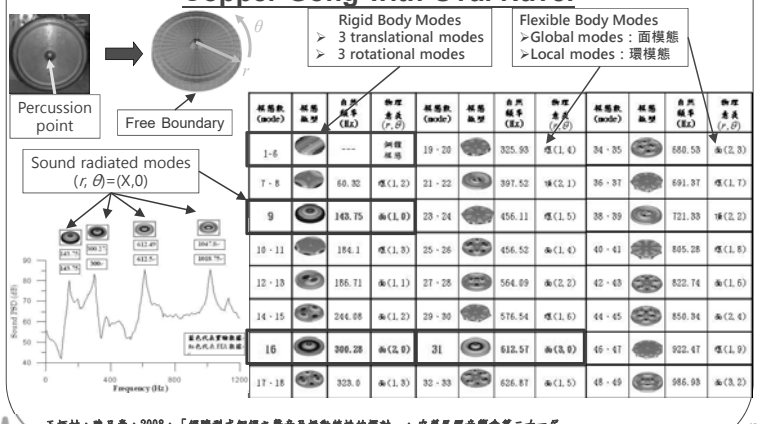
(a) Flange types of mode shapes (b) Web types of mode shapes



(c) Tyre types of mode shapes (d) Hub types of mode shapes



Sound and Vibration Correlation Study of the Copper Gong with Oval Navel

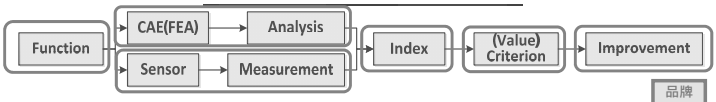


王相村，陳品豪，2008，「鐘腳型式銅鑼之聲音及振動特性的探討」，中華民國音響會第二十一屆學術研討會，台中，論文編號：A021。

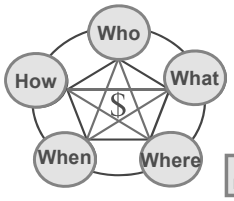
Outline

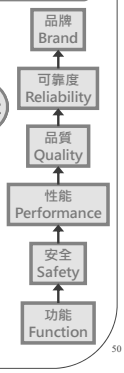
- 1. Introduction
- 2. Spirits of Industry 4.0
- 3. Fundamental Knowledge of Sound and Vibration
  - 3.1 System Block Diagrams for ISO and SPR
  - 3.2 Vibration and Dynamics
  - 3.3 Acoustics: Sound/Noise
  - 3.4 System – Sub-system – Component
- 4. General Approach
  - in Product Development and Improvement
- 5. NVH Diagnosis Approach
- 6. Conclusions and Recommendations

How to perform "Engineering Design" ?
"FCAICI" & "FSMICI"

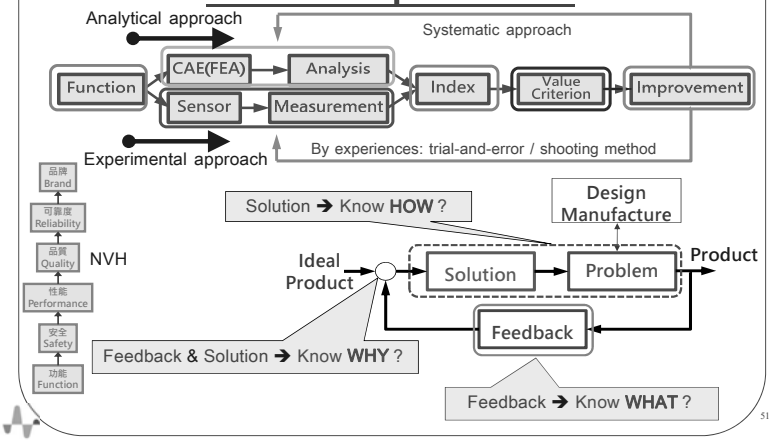


- Function : what "purpose"?
- Approach
  - Analytical approach
    - CAE
    - Analysis
  - Experimental approach
    - Sensor
    - Measurement
- Index : Performance Index (PI)
- Value ➔ Criterion :
  - From "Value" to acceptance "Criterion"
- Improvement : seek for proper solution

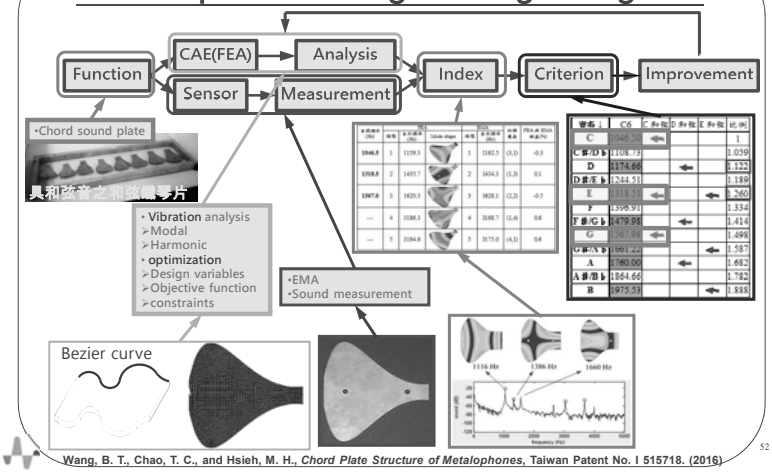




"FSMICI" & "FCAICI" Procedures for NVH improvement

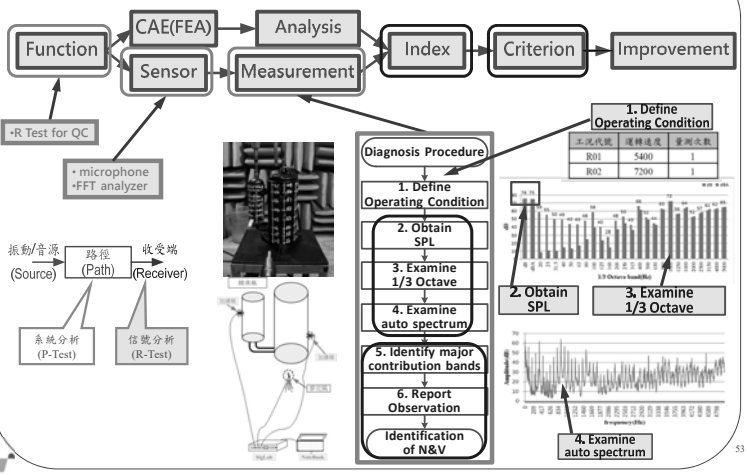


How to perform "Engineering Design" ?

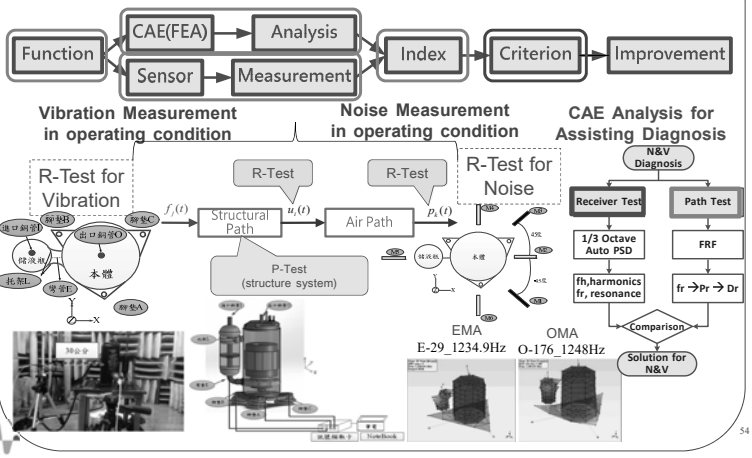


Wang, B. T., Chao, T. C., and Hsieh, M. H., *Chord Plate Structure of Metalophones*, Taiwan Patent No. I 515718. (2016)

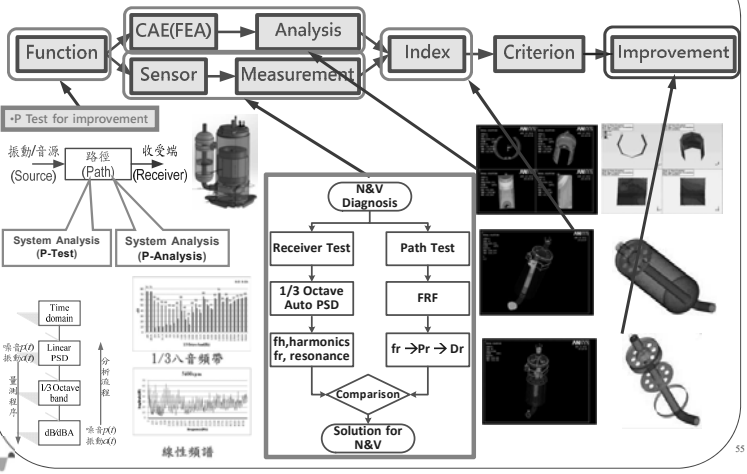
Noise Evaluation for Rotary Compressor



Noise Diagnosis and Improvement for Rotary Compressor

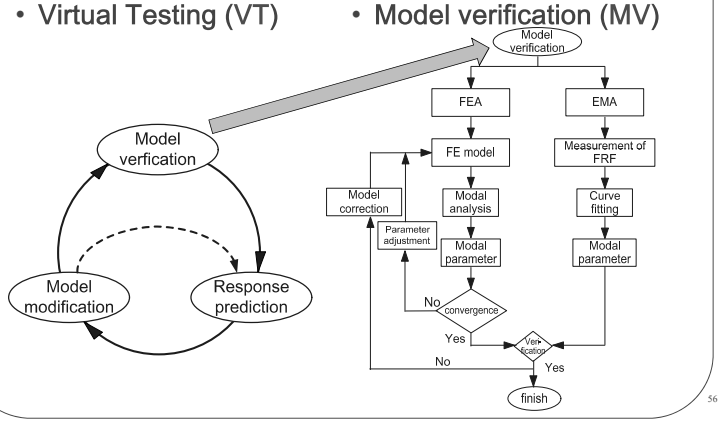


Noise Diagnosis and Improvement for Rotary Compressor



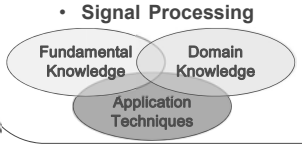
Virtual Testing (VT) for Product Design

- Virtual Testing (VT)
- Model verification (MV)



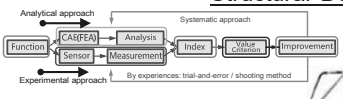
Vehicle Structural Design for NVH concerns

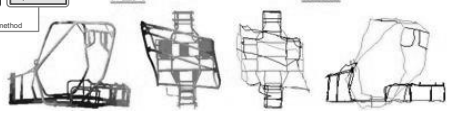
- **Fundamental Knowledge**
  - NVH:
    - noise, vibration, harshness
  - BSR:
    - buzz, squeak, rattle
  - CAE
    - P-analysis
    - R-analysis
    - Optimization
  - Instrumentation:
    - analyzer, acc., mic.
    - Signal Processing
- **Domain Knowledge**
  - Vehicle industry background
    - Engine, chassis, tire, suspension, frame, etc.
  - Vehicle dynamics
    - Accelerated, Braking, Handling, Ride quality, etc.
- **Application techniques**
  - Structural analysis
  - Structural testing
    - P-Test: EMA
    - R-Test for Sound & Vibration
  - Model Verification (MV)
    - Design Verification (DV)
  - Optimum design
    - Product Validation (PV)



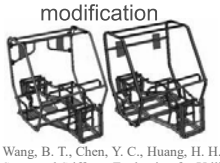
UV Frame Structure Virtual Testing

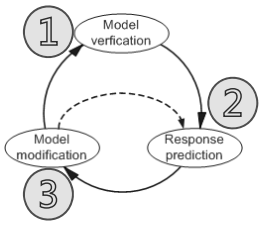
Structural Design Modification



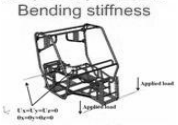


Structural design modification





Response prediction: Bending stiffness

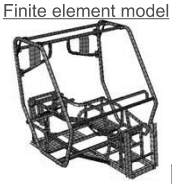


Torsion stiffness

Wang, B. T., Chen, Y. C., Huang, H. H., and Chen, Y. C., 2010, "Model Verification and Structural Stiffness Evaluation for Utility Vehicle Frame Structure," *The 25th World Battery Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition*, Shenzhen, K57HGP01.

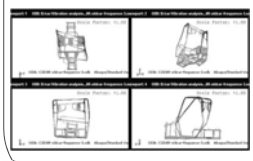
UV Frame Structure Virtual Testing (VT): Model Verification (MV)

Finite element model



UV frame structure

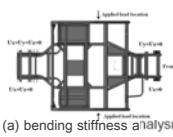
Mode shape via FEA



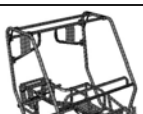
Mode shape via EMA

Wang, B. T., Chen, Y. C., Huang, H. H., and Chen, Y. C., 2010, "Model Verification and Structural Stiffness Evaluation for Utility Vehicle Frame Structure," *The 25th World Battery Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition*, Shenzhen, K57HGP01.

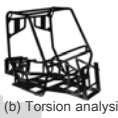
UV Frame Structure Virtual Testing (VT): Response Prediction (RP)



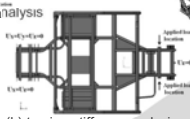
(a) bending stiffness analysis



(a) Bending analysis



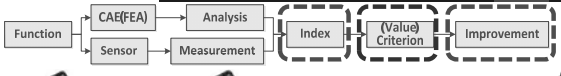
(b) Torsion analysis

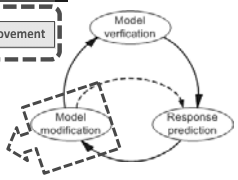


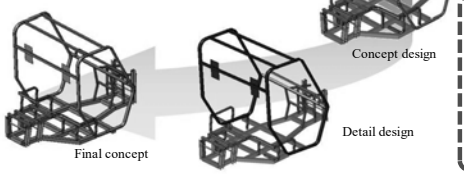
(b) torsion stiffness analysis

Wang, B. T., Chen, Y. C., Huang, H. H., and Chen, Y. C., 2010, "Model Verification and Structural Stiffness Evaluation for Utility Vehicle Frame Structure," *The 25th World Battery Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition*, Shenzhen, K57HGP01.

UV Frame Structure Virtual Testing (VT): Design Modification (DM)







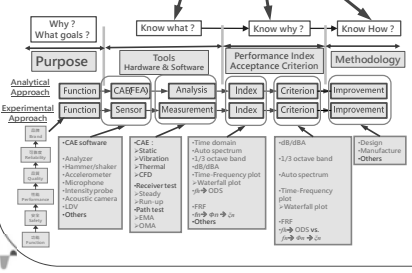
vehicle structure	Original	Optimum	Difference (%)
Bending stiffness (N/mm)	808	825	+2.15
Torsion stiffness (kN-mm /deg)	1,224	1,385	+13.18
Weight (kg)	104	85.6	-17.70

Wang, B. T., Chen, Y. C., Huang, H. H., and Chen, Y. C., 2010, "Model Verification and Structural Stiffness Evaluation for Utility Vehicle Frame Structure," *The 25th World Battery Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition*, Shenzhen, K57HGP01.

Outline

Approach to Product Design with N&V Concerns

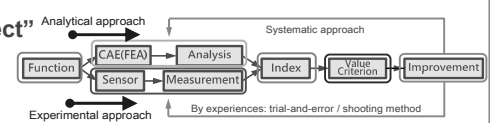
- **Feedback ability:**
  - Tools to "know what"
  - Technique to "know why"
- **Solution ability:**
  - Methodology to "know how"

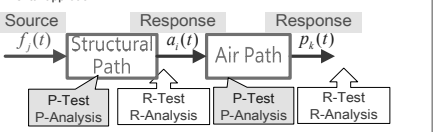


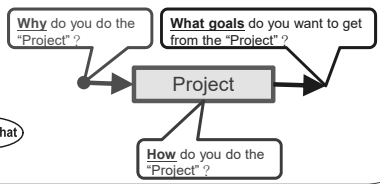
- **Fundamental knowledge**
  - Vibration/Dynamic
  - Acoustic (sound/noise)
- **Domain knowledge**
  - Percussion instruments
    - Musical theory
  - Air Conditioner
    - Compressor…
  - Vehicle
    - Engine and power transmission
    - Tire
    - Vehicle performance
    - Handling
    - Ride comfort/quality
    - Aerodynamic …

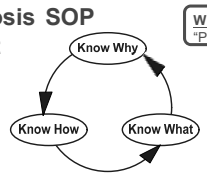
General Approach for NVH Diagnosis

- **1. Define the "Project"**
- **2. Think:**
  - Why to do?
  - What goals?
  - How to do?
- **3. Plan "How to do"?**
  - Know what?
  - Know why?
  - Know how?
- **4. Diagnosis SOP**
- **5. Report**



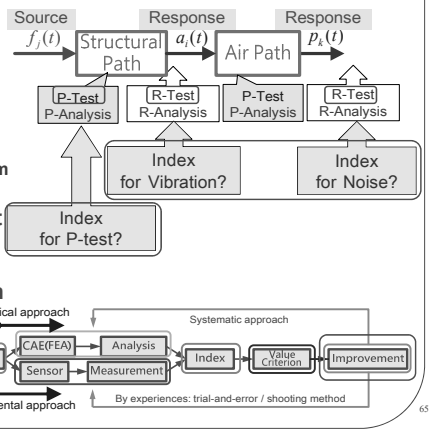






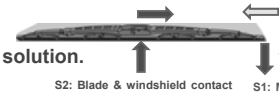
NVH Diagnosis Approach

- 4. Diagnosis SOP
  - R-test for S&V
    - Steady-state
    - Run-up / Coast-down
  - P-test (EMA)
    - For structure
      - Component → System
    - For air-structure
  - Compare R-test & P-test
    - Identify "resonance"
    - Identify "source"
  - DM, design modification
    - Experimental
    - Analytical
  - Repeat above



NVH Diagnosis for wiper noise

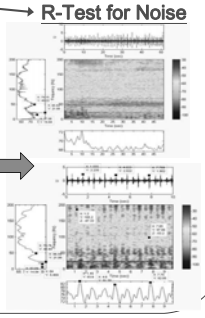
SPR analysis

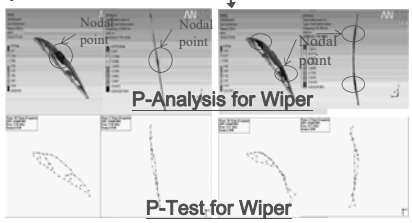


S2: Blade & windshield contact S1: Motor

- Define the project.
- Think "why" and "what goals".
- Plan "how to do".
- Carry on diagnosis to feedback and find solution.
  - Perform R-test.
  - Perform P-test (EMA).
  - Compare the results from R-test and P-test.
  - Seek for design modification (DM).
- Report solution and results.

R-Test for Noise



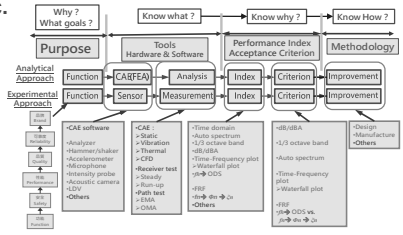


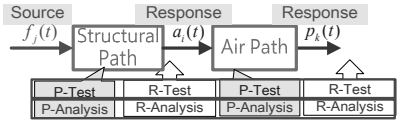
P-Analysis for Wiper

P-Test for Wiper

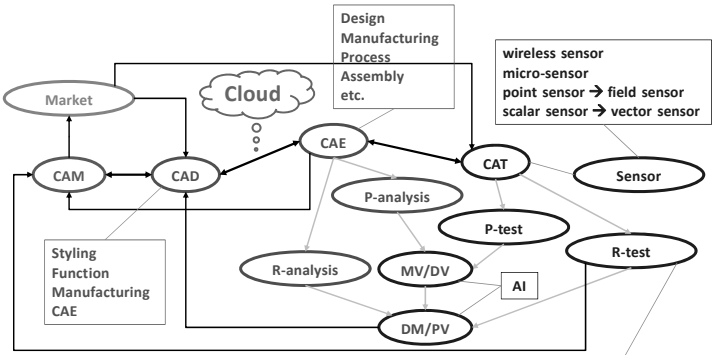
What are your available "know what" tools?

- Hardware for experiments
  - Analyzer, Sensors, etc.
  - Experimental ability
    - R-test for N&V
    - EMA for P-test
- Software for analysis
  - Analysis ability
    - Static
    - Vibration
      - Modal
      - Harmonic
      - Transient
      - Spectrum
    - Thermal
    - Vibro-acoustic
    - CFD
    - optimization





6. NVH Techniques Future Development base on Industry 4.0 Spirits



- "CPS" be "ALL in ONE"
- "IoT" be the "connection" among "ALL"

Smart monitoring
self-diagnosis
Objective oriented App

7. Conclusions

- NVH issues in engineering
- Spirit of "Industry 4.0": Feedback & Solution
  - (1) IoT → Feedback
    - Data → Information
      - Tools to "know what"
      - Technique to "know why"
  - (2) CPS → Solution
    - Testing → Virtual Testing
    - CAE → Experimental Verification
    - Verification → Validation
    - Component design → System design
      - Methodology to "know how"
- Fundamental knowledge
  - Vibration/Dynamic
  - Acoustic (sound/noise)
  - VT (Virtual Testing)
- Domain knowledge
  - Products?
- From "Component" to "System"
- System Concept
  - ISO
  - SPR
  - F →GMBI →R
- "FSMICI" & "FCAICI"
  - "know what" tools?
  - "know why" techniques?
  - "know how" methodology?
- NVH diagnosis approach
- Case study
  - NVH Diagnosis for wiper noise

Thank you for your attention.

AITA/NVH

Service – Innovation – Cultivation – **Inheritage**

「振動噪音產學技術聯盟」

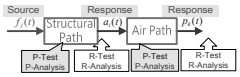
Academia Industry Technology Alliance for Noise, Vibration and Harshness (AITA/NVH)

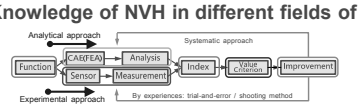
AITA NVH 服務 創新 深耕 傳承

服務：深入業界專業服務
創新：創意發想如山壯大
深耕：組織堅固信賴深耕
傳承：振動波般永續傳承

Noise and Vibration Techniques in Industry Application base on Industry 4.0

- Reveal my special & unique concepts, such as
  - SPR
  - ISO
  - FSMICI & FCAICI
  - Industry 4.0: feedback & solution
- Practical approach for NVH diagnosis and improvement
  - Concept about R-test for steady-state and run-up
  - Approach about P-test for determining structural modes,
  - CAE model for structural P-analysis → R-analysis
- Practical approach in defining problem
  - to carry out the project
- Background knowledges
  - Fundamental Knowledge of NVH
  - Domain Knowledge of NVH in different fields of engineering





Industry 4.0 for Product Development