中華民國汽車工程學會

第十四屆會員大會暨學術研討會議程表

【時間：106 年 05 月 13 日／地點：明道大學 寒梅大樓- 梅館 20A 演講廳】

時　　間	議程內容	演講人	主持人
09:00~09:30	報到時間(寒梅大樓－梅館 20A 演講廳) (新會員招募、新舊會員聯誼)		中華民國汽車工程學會 秘書處
09:30~09:50	大會開始 (主席報告、理事長致歡迎詞、明道大學郭秋勳校長致詞、來賓致詞)		中華民國汽車工程學會 林村基理事長 學術論文委員會主任委員 溫富亮教授
09:50~10:40	專題演講(一) **應用振動與噪音防制技術於車輛工程之發展趨勢**	國立屏東科技大學 機械工程系 王栢村教授	溫富亮教授
10:40~11:10	**第十四屆第一次會員大會暨第十四屆理監事改選(非會員來賓中場休息)**		
11:10~12:00	專題演講(二) **車輛售服產業 4.0－創新營運模式構想之簡介**	國立台北科技大學 車輛工程系 黃國修教授	明道大學管理學院 林原勗院長
12:00~12:30	午 餐 時 間		
12:30~13:30	**第十四屆常務理監事改選暨 第十四屆理事長及副理事長改選** 主持人: 林村基 理事長		分場報告人報到 中華民國汽車工程學會 秘書處
13:30~15:30	學會未來發展與展望	演講人: 劉英標所長	學術暨技術論文分場報告 主持人: 謝振中教授 主持人: 羅玉林教授
	自動駕駛汽車發展現況及展望	演講人: 黃靖雄教授	
	地點：梅館 20A 演講廳		寒梅大樓－梅 20 教室及梅 21 教室
15:30~15:45	新舊任理事長交接(恭請黃榮譽理事長監交) 地點：梅館 20A 演講廳		
15:45~	會議結束、校內參觀交流		

2017 National Conference on Vehicle Engineering and Advanced Energy Technology

Application of Noise and Vibration Technology to Development of Vehicle Engineering

Bor-Tsuen Wang

Department of Mechanical Engineering, National Pingtung University of Science and Technology, Pingtung, 91201, Taiwan

Wang, B. T., 2017, "Application of Noise and Vibration Technology to Development of Vehicle Engineering," 2017 National Conference on Vehicle Engineering and Advanced Energy Technology, Changhua, Taiwan, pp. 20-30. (Keynote speaker)
(ISBN 978-986-90643-0-9)

Application of Noise and Vibration Technology to Development of Vehicle Engineering

Bor-Tsuen Wang*

Department of Mechanical Engineering, National Pingtung University of Science and Technology, Pingtung, 91201, Taiwan

ABSTRACT

Noise and vibration (**N&V**) are important and critical issues in vehicle engineering. This work aims to provide an overview on how to deal with **N&V problems** and employ the spirits of **Industry 4.0**, i.e. **feedback** for **IoT** (Internet of Things) and **solution** for **CPS** (Cyber-Physical System). Six different stages of **engineering design** are introduced and related to vehicle design, particularly involving with **N&V** concerns. First, the **fundamental knowledge** regarding to solving **N&V** problem will be briefly discussed. Some important terminology for sound and vibration will be addressed. Both analytical and experimental approaches are systematically presented with conceptual block diagram, such as **SPR** (**Source-Path-Receiver**) and **ISO** (**Input-System-Output**) as well as system and component levels. The general procedure to perform engineering design, i.e. the numerical approach as "**FCAICI**" and the experimental approach as "**FSMICI**", is then proposed and shown to demonstrate the product development and improvement base on concept of "**feedback**" and "**solution**." The **N&V diagnosis** approach is also presented from the definition of the **N&V** problem and analysis objectives to the layout of dealing with N&V. Finally, the recommendation for future development of treating N&V issues inherently adopting **IoT** and **CPS** concepts is shown. This work may not address all of N&V aspects but provide the guide for engineers and managers to precede their works on N&V problems.

Keywords: Noise and vibration (N&V), Internet of Things (IoT), Cyber-Physical System (CPS), source-path-receiver (SPR), input-system-output (ISO).

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].

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.

For treating NVH problems, the solution techniques can be categorized into experimental and analytical/numerical approaches [3-5]. The TUD 1105 Year 1 WG1 task extended scientific report [6] presented the review on the state-of-the art of NVH techniques concerning Internal Combustion Engine (**ICE**) and Electric vehicle (**EV**). Although the NVH techniques can be commonly adopted for EV and ICE, the noise and vibration behaviors can be different, such as sources, structure of system, masking effect, etc.

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.

This work focuses on the NVH issue related to vehicle engineering. The fundamentals of **sound** and **vibration** will be introduced first. The general approach in dealing NVH problem to combine both analysis and experiment will be addressed by "**FSMICI**" and "**FCAICI**" procedures. In particular, the practical application to NVH diagnosis and improvement is then demonstrated with case studies. This work will hopefully provide with guidelines from the fundamentals of NVH to **feedback** and **solution** techniques in solving NVH problems.

* Corresponding author, email: wangbt@mail.npust.edu.tw

2. SPIRITS OF INDUSTRY 4.0

Industry 4.0 may have first been proposed by Germany in 2012, and **Productivity 4.0** is formulated in Taiwan. The development proposal for Productivity 4.0 was proposed by Executive Yuan of Taiwan in 2015 [8]. People agree that Industry 4.0 may bring about the **fourth industrial revolution**, and there are two major issues for Industry 4.0: **Internet of Things** (**IoT**) and **Cyber-Physical Systems** (**CPS**) [9]. Base on the spiritual concept of Industry 4.0, this paper proposes two keywords, i.e. **Feedback** and **Solution**.

Figure 1(a) may simply define the production process that the raw material is input to the factory and made for the product via design and manufacture. Figure 1(b) includes **Feedback** and **Solution** into the production process. The product information from the market is feedback to compare with the ideal product so as to seek for the solutions for design and manufacture as required. The abilities to **Feedback** and **Solutions** for design and manufacture are critical and defined as follows:

1. **Feedback**: the ability to collect and analyze the product information either in the development stage or even in the market. There must have the mechanism in sensing and collecting data as well as analyzing data to provide useful information for product improvement or other purposes.
2. **Solution**: the ability to solve for the needs and problems from feedback information about the product either in design or manufacturing stage. The analysis and testing skills for product design on the **design verification** (**DV**) and **product validation** (**PV**) are essential issues, and so are manufacturing aspects, such as smart and flexible manufacturing, etc.

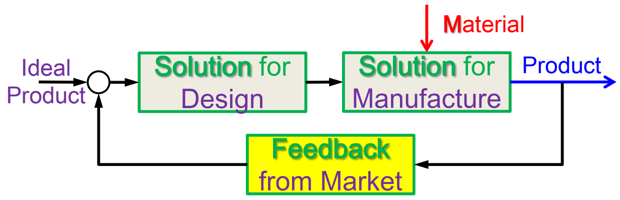
For **the spirits of Industry 4.0**, **Feedback** is basically for **IoT** and **Solution** is for **CPS**. Figure 2 shows another perspective for product development process with **Feedback** and **Solution**. There may have three steps:

1. **Feedback**: the information may come from the market investigation or from the product testing during design or manufacture. The proper product specification can be well defined base on the feedback information.
2. **Design**: the design can be preceded according to the specification, and the sample or prototype of product can be fabricated. **Design verification** (**DV**) and **product validation** (**PV**) must be carried out either numerically or experimentally to ensure the product will meet the specification.
3. **Manufacture**: only the product is passed for **DV** and **PV**, then the product can be in mass production and export to the market.

The production process from **Feedback**, **Design** to **Manufacture** can be iterative until the right product made for the market. One can observe that Figure 2 shows above three stages of product development process and conforms to Figure 1(b). In summary, **Feedback** needs the **IoT** infrastructure, while **Solutions** for design and manufacture need different **CPS** elements.

Figure 3 reveals six different stages of **engineering designs**, i.e. design for **function**, **safety**, **performance**, **quality**, **reliability** and, finally, the **brand**. 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. As shown in Figure 4, the vehicle system can contain lots of sub-systems. Almost all of the sub-systems are involved with NVH issues. This work do not intend to cover all the aspects for vehicle design related to NVH but lay out the fundamentals of **sound** and **vibration** as well as the systematic approach in dealing NVH problems as the guidelines for engineers.

(a) Simple production process



(b) Production process with feedback and solution

Figure 1: Production process. (a) without feedback and solution, (b) with feedback and solution.

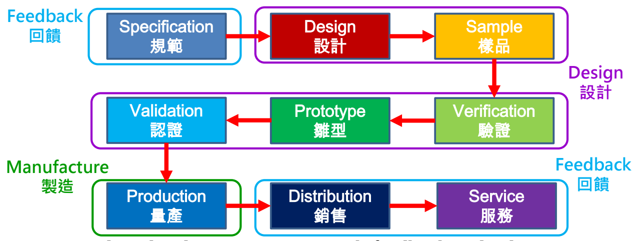


Figure 2: Product development process with feedback and solution.

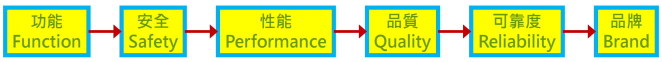


Figure 3: Six different stages of engineering design.

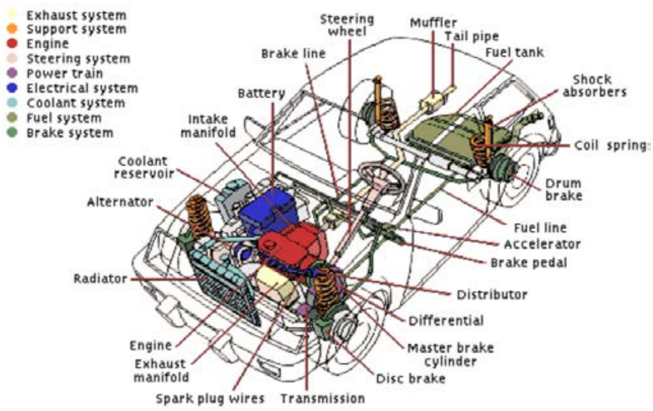


Figure 4: Overview of vehicle system: http://schoolworkhelper.net/vehicle-systems-overview/

3. FUNDAMENTAL KNOWLEDGE OF SOUND AND VIBRATION

This section will briefly introduce the theoretical background of sound and vibration. **Section 3.1** shows different aspects of system block diagrams. **Sections 3.2** and **3.3**, respectively, show important terminology for vibration and acoustic analysis. **Section 3.4** illustrates the important concept about system consisting of sub-systems and components.

3.1 System block diagrams for ISO and SPR

Figure 5 shows the system block diagram from different aspects. Figure 5(a) is the "**ISO**" block diagram where ISO is known as **input-system-output**. Another point of view for system block diagram is **SPR** as shown in Figure 5(b). The common way to interpret SPR is **source-path-receiver**, in which **receiver** is also equivalent to **response**.

Figure 5(c) can be simply shortened as "**F→GMBI→R**". **F** stands for force, i.e. **loading conditions** including the time variant loads and system initial conditions. The types of forces or loadings can be the concentrated force or moment, pressure, etc. Other than the **force type loadings**, the base excitation input can also be modeled by **displacement type** of input as well as velocity or acceleration depending on the requirement of practical system. Typical loadings for a vehicle can be the equivalent tire forces, engine mounting loadings, pavement surface inputs, aerodynamic forces, etc.

Regarding to the system, **GMBI** are key system parameters to be specified and discussed as follows:

1. **Geometry**: A structural system needs clear definition for its geometry shape and dimensions.
2. **Material**: Each part or sub-system of structure system requires the appropriate **material model** to simulate every component and up to sub-system and system level. The most typical and simple material model is **isotropic**, where **Young's modulus** and **Poisson ratio** of material are basic parameters. For vibration and dynamic analysis, the **density** of materials is also required.
3. **Boundary**: The system boundary conditions can be straight forward; however, the assumption of boundary needs to be carefully defined to simulate actual boundary and obtain the equivalent boundary conditions properly.
4. **Interface**: The interface means to describe the behavior between joint parts or mounting condition between components. The jointed members can be treated as welding, bolt jointed, adhesive, sliding contact, etc. The joint interfaces among all components need clear definition for all of the interacting interfaces between one and another component.

R is the **response** referred to the output of the system. Typical interest items in structural mechanics are displacement, strain, stress, velocity, acceleration, reaction force, etc.

Figure 6 shows the **SPR** diagram for noise and vibration (**N&V**). The key features in Figure 6 are summarized as follows:

- For structural related N&V, there are two paths, including **structural path** and **air path**.
- The **source** is specified as $f_j(t)$ in Figure 6 representing the input of the system where *j* implies the location and direction of force.
- The **vibration** response at the structure can be the displacement output, $u_i(t)$, while the **noise** response in the air is the sound pressure, $p_k(t)$.
- The **R-test** or **R-analysis** can be performed on the structure only or involving the air path to determine structural vibration or sound response via either experimental test (**R-test**) or analytical/numerical solution (**R-analysis**).
- The **P-test** or **P-analysis** is the system analysis and can be done by experimental or analytical/numerical approach. For **P-test** on structure, **experimental modal analysis (EMA)** is the typical method.

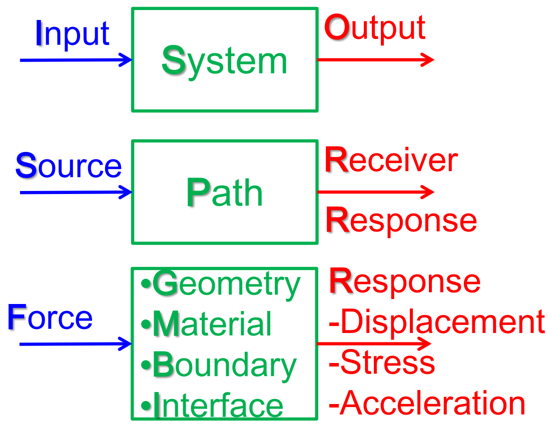


Figure 5: System Concept block diagram. (a) ISO, (b) SPR, (c) F→GMBI →R.

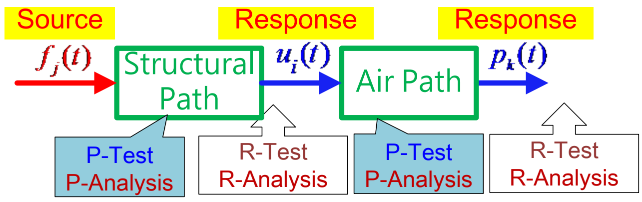


Figure 6: SPR diagram for noise and vibration (N&V).

Figures 7(a), 7(b) and 7(c), respectively, show the **physical** domain, **modal** domain and **frequency** domain for the **system block diagrams** of **air-structure system** [11]. Figure 7(a) shows the system block diagram of **air-structure system** in **physical** domain. The dotted line block in Figure 7(a) represents the **structure-only system** which equations can be expressed as follows:

$$[M_s]\{\ddot{u}\}+[C_s]\{\dot{u}\}+[K_s]\{u\}=\{F_s\}+[R]\{p\} \qquad (1)$$

where $[M_s]$, $[C_s]$, $[K_s]$ and $[R]$ are the structural mass, damping, stiffness and vibro-acoustic coupling matrices, respectively; $\{u\}$, $\{\dot{u}\}$, and $\{\ddot{u}\}$ are the displacement, velocity, and acceleration vector on the structure; $\{p\}$ is the acoustic pressure vector. The $[R]$ term in Eq. (1) is not effective for the structure-only system.

The **air-path system** equations can be expressed as follows:

$$[M_f]\{\ddot{p}\}+[C_f]\{\dot{p}\}+[K_f]\{p\}=\{F_f\}-\rho_0[R]^T\{\ddot{u}\} \qquad (2)$$

where $[M_f]$, $[C_f]$ and $[K_f]$ are the air (fluid) mass, damping and stiffness matrices, respectively; ρ_0 is the air density, and the associate term represents the air-structure interface loading to the air; $\{F_f\}$ is the acoustic loading vector. The integrated **air-structure system** equation can be derived as follows:

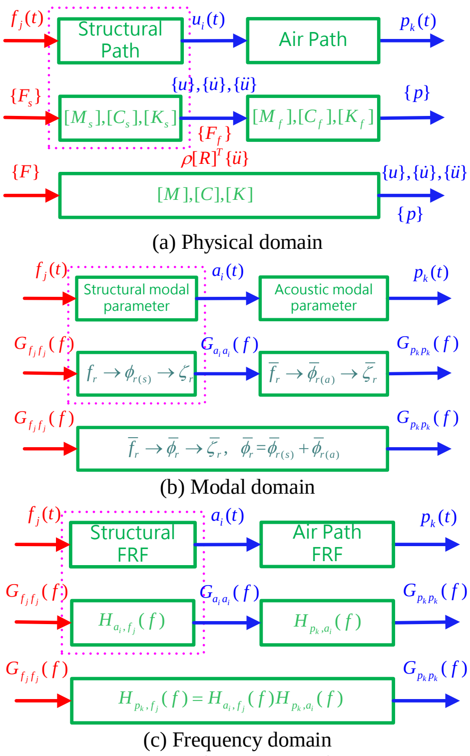


Figure 7: System block diagram of air-structure field analysis [11].

$$\begin{bmatrix} [M_s] & 0 \\ \rho_0[R]^T & [M_f] \end{bmatrix} \begin{Bmatrix} \{\ddot{u}\} \\ \{\ddot{p}\} \end{Bmatrix} + \begin{bmatrix} [C_s] & 0 \\ 0 & [C_f] \end{bmatrix} \begin{Bmatrix} \{\dot{u}\} \\ \{\dot{p}\} \end{Bmatrix} + \begin{bmatrix} [K_s] & -[R] \\ 0 & [K_f] \end{bmatrix} \begin{Bmatrix} \{u\} \\ \{p\} \end{Bmatrix} = \begin{Bmatrix} \{F_s\} \\ \{F_f\} \end{Bmatrix} \quad (3)$$

or in the simple expression:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{f\} \quad (4)$$

For the **structure-only system**, the $[R]$ term in Eq. (1) can be ignored such that Eq. (1) has the same form as Eq. (4). For harmonic response analysis, the harmonic solutions of $\{f\}=\{F\}e^{i\omega t}$, $\{u\}=\{U\}e^{i\omega t}$ and $\{p\}=\{P\}e^{i\omega t}$ can be assumed and so forth the system equations can be formulated as follows:

$$\left[([K]-\omega^2[M])\right]\{X\}+i\omega[C]\{X\}=\{F\} \quad (5)$$

where $\omega = 2\pi f$. ω is the frequency in rad/sec and f in Hz. By ignoring the force vector and neglecting damping term, the undamped structure-only system **natural frequencies** f_r and corresponding **mode shapes** $\phi_{r(s)}$, or simply denoted ϕ_r **,** can be obtained as shown in Figure 7(b). Note that the **modal damping ratio** ζ_r can only be determined from experiments. If the **air-structure system** is considered, the system modal parameters are shown as $\bar{f}_r$ **,** $\bar{\phi}_r$ and $\bar{\zeta}_r$ **,** respectively. It is noted that both the **structure-only natural frequency** f_r and the **air-structure natural frequency** $\bar{f}_r$ are different theoretically. While ϕ_r designates the **structural displacement mode shape**, $\bar{\phi}_r$ is referred to the **air-structure system mode shapes** that can contain the **structural displacement mode shape** $\bar{\phi}_{r(s)}$ and the **air acoustic mode shape** $\bar{\phi}_{r(a)}$ **,** i.e., the **radiated sound pressure mode shape**.

Referring to Figure 7(c) in the aspect of **frequency** domain, one can measure the acceleration at i location designated $a_i(t)$ and the sound pressure at k location $p_k(t)$ when the point force is applied at j location $f_j(t)$. In experiments, one can measure $H_{a_i,f_j}(f)$, which is the **frequency response function** (**FRF**) between $f_j(t)$ and $a_i(t)$, and $H_{p_k,f_j}(f)$ the **FRF** between $f_j(t)$ and $p_k(t)$, respectively. The FRFs can be obtained, respectively, from simulation and experimental modal analysis (**EMA**), i.e. **P-analysis** and **P-test**.

It is noted that there are **two types of R-tests**, i.e. **R-test** for **vibration** and **R-test** for **sound**. The conventional sensors for **vibration** and **sound** measurement are **accelerometers** and **microphones**, respectively. Other than time domain response $a_i(t)$ and $p_k(t)$, the interested quantities are the auto **power spectral density** (**PSD**) functions $G_{a_i a_i}(f)$ and $G_{p_k p_k}(f)$.

3.2 Vibration and dynamic

Both **vibration** and **dynamic** are nearly equivalent and base on the Newton's Second Law. Structural vibration can be viewed as **microscopic** point of view, while structural dynamic is **macroscopic**. For example of **vehicle dynamic**, the accelerating and braking performance of vehicle are analyzed to characterize the vehicle motion. The **vehicle vibration** is generally referred to structural local vibration due to incurred external excitation on the vehicle structure. In fact, either vibration or dynamic analysis can be categorized with four types of analysis. Wang [12] details the procedures and theoretical formulations for four types of vibration analysis of continuous system. Figure 8 shows the system block diagram for **four types of vibration analysis**.

1. **Modal Analysis (MA)**: Structural **modal parameters**, including **natural frequency**, **mode shape** and **modal damping ratio**, can be obtained from modal analysis via experiment or analysis. It is noted that modal damping ratio can only be determined through experiments. Modal parameters are the system information in modal domain. Either theoretical modal analysis (**TMA**) or experimental modal analysis (**EMA**) can be carried out and termed as **P-analysis** or **P-test**, respectively.
2. **Harmonic Response Analysis (HRA)**: Two important indices, i.e. **frequency response function (FRF)** and **operational deflection shape (ODS)**, can be obtained from harmonic response analysis. Base on the assumption of harmonic excitation, the steady state response will also be harmonic. The **FRF** or **transfer function** between the specified input and interested output can be determined. Noted that obtaining FRF is **P-analysis** or **P-test**, because **FRF** is the system property regarding the **transfer path analysis (TPA)**. The **ODS** can be viewed as the steady state response of system output and so forth obtaining **ODS** is a type of **R-analysis** or **R-test**.
3. **Transient Response Analysis (TRA)**: **TRA** is a kind of **R-analysis**. If the experimental approach is adopted to measure the time domain system response, i.e. **R-test**. From **ISO** or **SPR** block diagram, one should define the

input for loadings and the complete system information before **TRA** and can obtain structural transient response output verse time.

4. **Spectrum Response Analysis (SRA)**: When the system is subject to the inherently random type of input such as irregular random pavement surface excitation, the frequency domain analysis, i.e. **SRA**, is generally adopted instead of **TRA** for efficient and effective solution.

Figure 9 shows the study of **3-DOF vibration system** of a **quarter car model**. The analytical approach starts from the **mathematical model** of the quarter car with 3-DOF, i.e. driver, sprung mass and un-sprung **mass**. And those connections include **springs** and **dampers** for seat, suspension and tire, respectively. The system equation can be the coupled ordinary differential equations as shown for typical base excitation MDOF system. The analytical solutions from **MA**, **HRA**, **TRA** and **SRA** are, respectively, revealed.

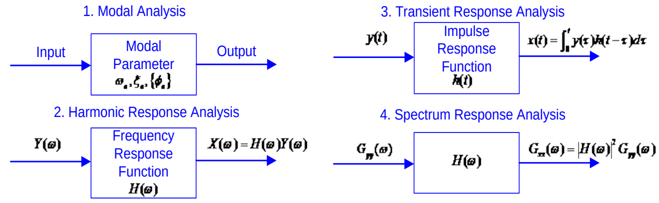


Figure 8: System block diagram for four types of vibration analysis.

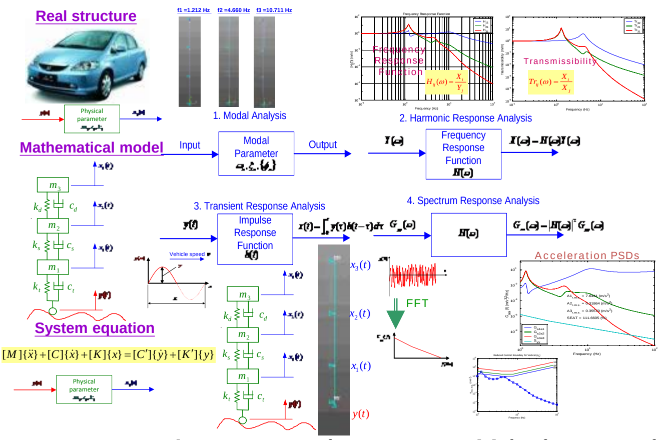


Figure 9: 3-DOF vibration system of quarter car model for four types of vibration analysis.

3.3 Acoustics: sound/noise

Acoustics is the science to study **sound**, and **noise** can be considered when the sound is unwanted, undesirable, disturbance, annoyance, etc. Sound generation mechanism can be simply divided into two types, i.e. **flow-induced sound** and **structural vibration induced sound**. From KangXiZiDdian, an ancient Chinese Dictionary, sound generation is described as the interaction between **flow** and **body**. This physical phenomenon is well interpreted. The other way to examine the sound propagation is the **structure-borne** sound and **air-borne** sound.

The basic physical parameter to characterize sound is the **sound pressure**, i.e. the atmosphere pressure fluctuation due to disturbance. When we use microphone to measure the sound, the time response of the atmosphere pressure fluctuation $p(t)$ is recorded as shown in Figure 10. One should note that sound can propagate along space. Figure 11 depicts a harmonic sound wave $p(x,t)$ in time and spatial domains. Some terminologies are also noted in Figure 11.

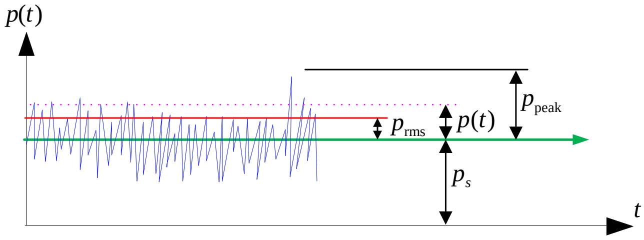


Figure 10: Sound pressure response in time domain.

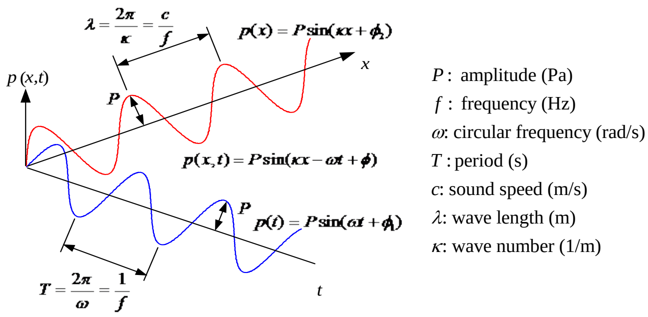


Figure 11: Harmonic sound wave in time domain and spatial domain.

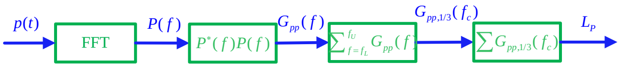


Figure 12: Signal process block diagram for sound pressure.

Figure 13: Example for typical signal processing of sound pressure.

The sound pressure is in Pa and generally expressed by **sound pressure level (SPL)** defined as follows:

$$L_P = 20\log\left(\frac{P}{P_{ref}}\right) \tag{6}$$

where P is the measured sound pressure, and $P_{ref} = 20\times10^{-6}\,\text{Pa}$ is the reference sound pressure that is considered the hearing threshold of human ear. The unit of **SPL** is dB *re* $20\times10^{-6}\,\text{Pa}$.

It is also noted that the sound pressure response $p(t)$ can be measured and processed to obtain its quantities in frequency domain. Figure 12 shows the signal process to obtain **Fourier spectrum** $P(f)$, **auto PSD spectrum** $G_{PP}(f)$, **1/3 octave band spectrum** $G_{PP,1/3}(f_c)$ and **SPL** L_P from the time domain data $p(t)$. Figure 13 is some typical signals. Note that the overall **SPL** accounts for all frequency effect and can be expressed by **dB** or **dBA**. **dB** is the summation of SPL at all of central frequency f_c without weighting, while dBA is the A-weighted SPL. Figure 14 depicts the measured 1/3 octave band spectrum and the A-weighted SPL distribution.

In addition to the **sound pressure level (SPL)**, two other fundamental indices for sound are **sound intensity level (SIL)** and **sound power level (SWL)**. It is noted that **sound intensity** can be experimentally measured by the intensity probe that consists of two microphones, while **sound power** can only be measured indirectly from sound pressure or sound intensity.

Figure 15 shows a typical time-frequency plot obtained by **short time Fourier transform (STFT)**. Such a signal process is also known **order tracking analysis**. Some other techniques to analyze signal's time-frequency properties include **wavelet transform**, **Hilbert transform**, etc. Among all of those quantities shown in Figure 12 for sound analysis, they are indices for **R-test** and can also be obtained from numerical simulation, i.e. **R-analysis**.

3.4 System – Sub-system – Component

As we discuss about the system characteristics of structural vibration and sound generation mechanism in previous sections, one should note that the vehicle system can contain a lot of sub-systems as shown in Figure 4. Almost all of the sub-systems are involved with NVH issues. Figure 5(c) addresses the important concept about the system, i.e. **GMBI**. In examining the system or sub-system **N&V** phenomenon, engineer should keep in mind about the system parameters including **GMBI**. Engineer may decouple the system to several sub-systems or components to do analysis or testing. Although **Geometry** and **Materials** are the same with no doubt, **Boundary** and **Interface** may alter their conditions from system to sub-systems or components. Engineer should be careful in evaluating system response to consider whether the structure is in system level, sub-system level or component level. When different levels of a structure system are to be compared, the system parameters, i.e. **GMBI**, should be equivalent in priori.

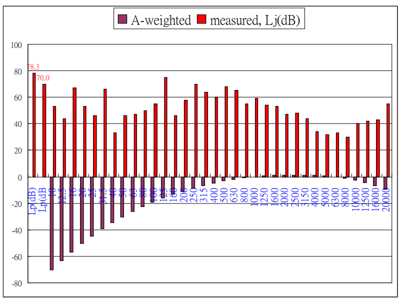


Figure 14: Example of measured 1/3 octave band spectrum and calculation of dB and dBA.

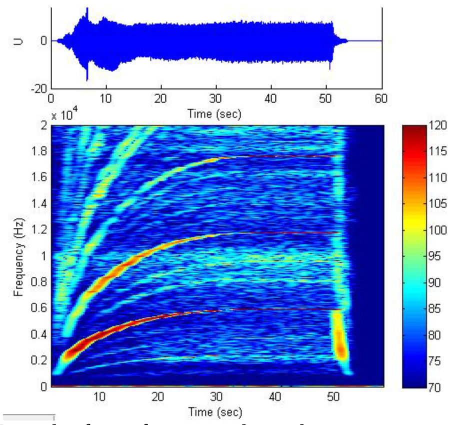


Figure 15: Example of time-frequency plot analysis.

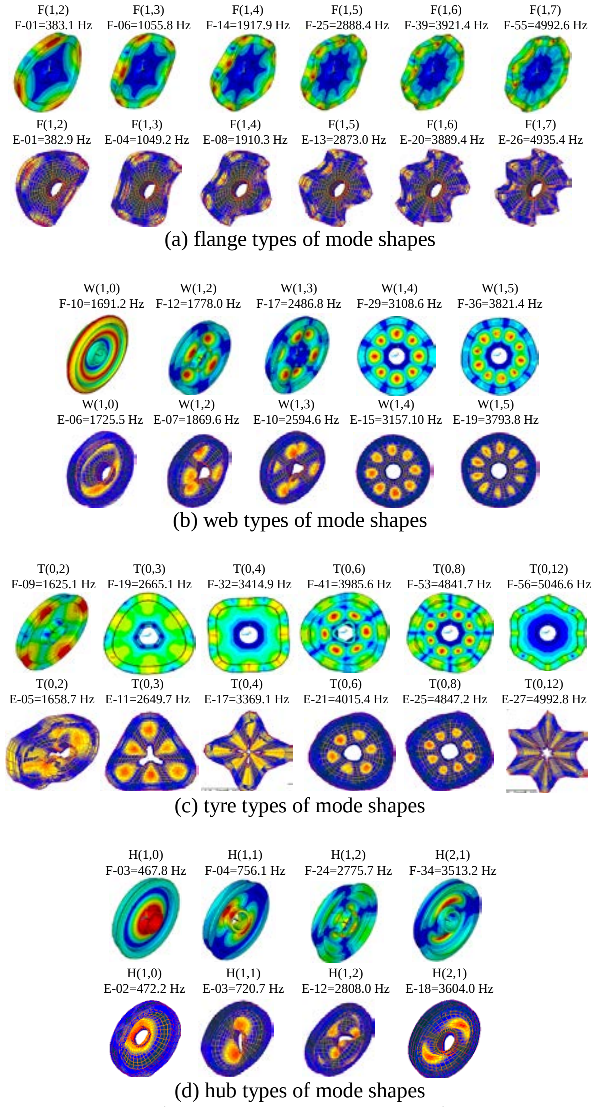


Figure 16: Example of global modes and local modes for a steel track wheel [13].

The followings show the interpretation of structural vibration modes. There are two types of vibration modes: **rigid body modes** and **flexible body modes**. For rigid body modes, there are **three translational modes** and **three rotational modes**. The flexible body modes can contain **global modes** and **local modes**. Figure 16 shows the example of vibration modes for the steel wheel in free boundary condition, and only those flexible body modes are revealed [13].

- Figure 16(a) shows the **flange** type of modes that are actually the **global modes** of the wheel.
- Figure 16(b) shows the **web** type of modes in which only web vibrates and flange and hub are hardly moved. The web-vibration only is the **local modes** of vibration.
- Figure 16(c) shows the **tyre** type of modes that the tyre vibrates radially and incurs the else parts of wheel also vibrating accordingly. Nevertheless, the tyre modes can be categorized the **local modes** in nature.
- Figure 16(d) shows the **hub** type of modes that are also the **local modes**. The hub vibrates and incurs the motion of web, while the flange nearly does not vibrate.

From Figure 16, the important concept is that the assembly structure system has its vibration modes that can be distinguished as **global modes** and **local modes**. When the sub-system or component were tested or analyzed, the component's vibration modes may not be directly linked to the assembly structure system because the **Boundary** and **Interface** are different inherently. In summary, either R-test/P-test or R-analysis/P-analysis can be conducted to characterize the system, sub-system and component levels. The comparative study among different levels of the same system should be aware of the **equivalent condition of the structures**, i.e. the equivalent **GMBI**.

4. GENERAL APPROACH IN PRODUCT DEVELOPMENT AND IMPROVEMENT

Product development requires design verification (**DV**) and product validation (**PV**) to ensure the product can fulfill the requirement for its **function**, **safety**, **performance**, **quality** and **reliability** in different engineering design aspects of concerns as shown in Figure 3. Once the product can meet those five characteristics, the **brand** image can be built and value-added.

During the product development, Figure 17 proposes both analytical/numerical and experimental approaches in a systematic way, not only for treating NVH problems but also suitable for general engineering design cases. From Figure 17, the analytical and numerical approach can be abbreviated as "**FCAICI**" and the experimental approach as "**FSMICI**", respectively. The steps to adopt the procedures are discussed as follows:

1. **Function**: When a task or project is undertaken, engineer has to clearly define the purpose of the task. The tip is to clarify "**why to do the task?**" and "**what goals to achieve after the task?**" In other words, engineer has to define the problem and the project's objectives. Then, engineer can start planning the following works accordingly.
2. **Index**: Before proceeding analytical/numerical or experimental approach on the predefined problem, one must know what "**index**" to be evaluated. For example, the **SPL** is frequently used to judge the product noise condition.
3. **Criterion**: There must be some acceptance "**criterion**" corresponding to the index, e.g. **SPL** is less than 70 dBA. Here **SPL** is the **index**, and **70dBA** is the **criterion**. Noted that one can obtain the corresponding value of the index and check if the value meets the criterion. If not, the improvement procedure needs to be conducted in the next step.
4. **Improvement**: If the product exceeds the acceptance criterion, the improvement action must be taken. How to select the action for NVH improvement may be based on engineer's experiences. However, there have software and hardware tools available to assist engineers to accomplish their task effectively and efficiently and can be carried out either analytically/numerically or experimentally.
5. By **analytical** or **numerical** approach, two steps are suggested.
   (1) **CAE**: Nowadays, many computer aided engineering (**CAE**) software, such as finite element method (**FEM**) or boundary element method (**BEM**) base, are available for solution of NVH problem. Engineer must know the availability in the company and the ability to apply CAE software to determine the value of index.
   (2) **Analysis**: As discussed in Section 3, there are four types of typical analysis for vibration and similarly for sound analysis. Of course, mathematical modeling is required in order to pursuit the target problem as well as the proper application of CAE to obtain the index's value. Noted that **Model Verification** (**MV**) is necessary to ensure the simulation analysis being correct or at least reasonable. Therefore, the systematic study on the target problem can be carried on and different improvement actions can be virtually tested, i.e. **Virtual Testing** (**VT**). For example, to predict the product's SPL can be the main task known as **Response Prediction** (**RP**).
6. By **experimental** approach, two basic steps are involved.
   (1) **Sensor**: Engineer has to know what "sensor" is available and can be used and so forth to measure the prescribed index's value. **Sound Level Meter** is the device to obtain **SPL** in dBA. Here, "sensor" designates the sensing device just a general term, i.e. engineer must have the knowledge in using various kinds of sensors in conjunction with measurement devices/hardware as well as the ability to do testing and experiment in order to measure the index as desired.
   (2) **Measurement**: Engineer should know about the operation and procedure of instrument as well as the operating condition of target product, so as to correctly determine the value of index. Every index has its physical meaning and testing procedure that may be regulated by standards. Engineer is responsible for doing the right test.

Although the analytical/numerical and experimental approaches are stepped as "**FCAICI**" or "**FSMICI**", the above mentioned procedures are suggested for practical application. Selecting and defining the proper "**index**" is the next step right after "**function**" for the definition of problem and analysis objective. By either going through numerical solution or experimental work, one can obtain the "**index's value**" first and judge if the value is within the acceptance "**criterion**". The "**improvement**" action can then be conducted by analysis or experiments. The important tip is to stick with the "**index**." No matter what the improvement action made, engineer can judge the effectiveness of improvement base on the index's value in comparison to the criterion.

There may have other indices to be evaluated as well. For example, in judging the **SPL** that comes from sound pressure level distribution in the one-third octave band, engineer may also need to examine **one-third octave band spectrum** or even the **auto PSD spectrum**. Both spectra can be viewed as indices too and provide the clue to make the improvement.

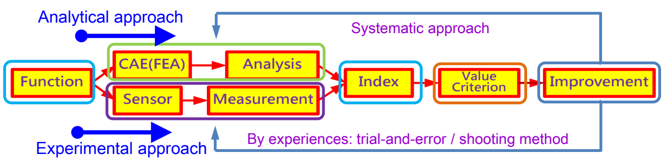


Figure 17: Analytical approach "FCAICI" and experimental approach "FSMICI" Procedures for NVH improvement.

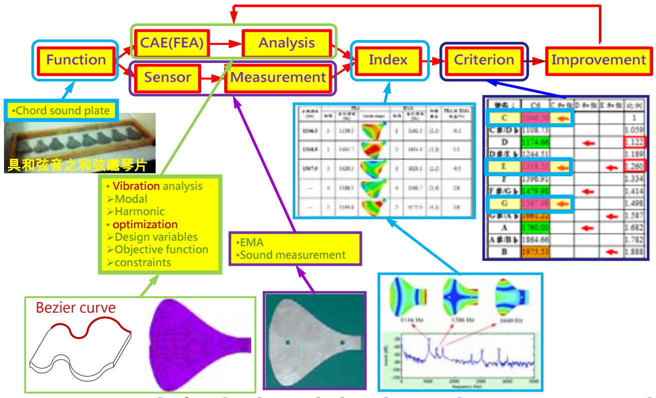


Figure 18: Example for chord sound plate design adopting "FCAICI" and "FSMICI" Procedures [14, 15].

Figure 18 shows the example by adopting "**FCAICI**" and "**FSMICI**" Procedures for the chord sound plate design. The design process is discussed as follows:

1. **Function:** The idea of **chord sound plate** (**CSP**) [14, 15] is to strike the plate that can produce triad chord sound, such as C major chord having the musical notes: C, E and G. The design goal is to find the plate geometry that can have the structural vibration modes with natural frequencies corresponding to standard frequencies of C major chord. The proper striking location needs prescribed properly to be able to excite the desired modes of vibration.
2. **Analytical approach:** the design analysis is carried out by FEA software. First, the forward analysis on a predefined shape of plate is carried out for **modal analysis** and **harmonic response analysis**. The inverse design of geometry parameters employing **Bezier curve** for shape optimization can then be followed to obtain the primary design of **CSP**.
3. **Index:** for the CSP design, structural **natural frequencies** and **mode shapes** are indices. The CSP design must have three vibration modes which natural frequencies will meet the requirement of musical note's frequencies. The mode shapes are also examined for selecting the proper striking location.
4. **Criterion:** the acceptance criterion is based on the errors of natural frequencies of vibration modes for CSP to be within 0.34% in comparison to the standard frequencies of musical notes.
5. **Improvement:** the optimization process through numerical simulation is conducted to find different geometry shapes and dimensions iteratively such that the final design of **CSP** has the natural frequencies conforming to the required criterion.
6. **Experimental approach:** the designed CSP is manufactured and performed **EMA** to obtain structural **modal parameters**, i.e. natural frequencies and mode shapes. Model Verification (**MV**) is carried out to calibrate the FE model, and Design Modification (**DM**) can be executed accordingly. In addition, the percussion sound measurement, i.e. **R-test** for **sound**, is also conducted to prove the success of **CSP** design.

The above procedures are adopted to demonstrate the process in structural design base on special sound effect. The "**FCAICI**" and "**FSMICI**" approaches can be applied to vehicle design as well as other products involved with sound and vibration concerns.

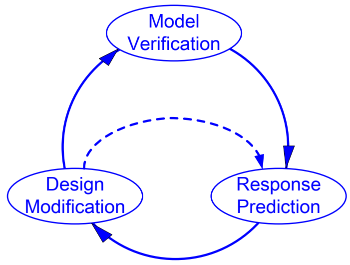


Figure 19: Virtual Testing (VT) procedures for MV, RP and DM.

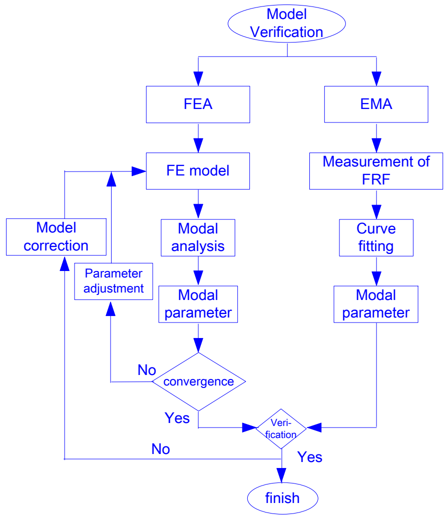


Figure 20: Procedures for Model Verification (MV).

Figure 19 shows **Virtual Testing** (**VT**) procedures that can be another point of view on structural design for either **NVH concerns** or other purposes. There are three steps of iterative process for **VT**, i.e. **MV**, **RP** and **DM**. Discussions are as follows:

1. **Model Verification (MV):** MV is to verify the numerical model that should be equivalent to the real structure system. The procedure to perform MV is shown in Figure 20. The main idea is that system's **modal parameters** should be consistent between numerical model and real structure.
2. **Response Prediction (RP):** when the numerical model is verified, i.e. the system model is equivalent to the real structure. With the assumption of input for loading conditions, the solution for response prediction (**RP**) can then be made. Here, **RP** is to numerically determine the index's value, so-called **R-analysis**. Engineer needs to do **R-test** to validate the results of **R-analysis** as well.
3. **Design Modification (DM):** As **R-analysis** and **R-test** are well calibrated for response prediction, the numerical model can be applied to **DM**, i.e. **model modification**. The numerical model consisting of **Geometry** and **Material** or even **Boundary** and **Interface** can be modified to predict the response due to the change of **GMBI**. **DM** and **RP** become an iterative process until the satisfied **DM** on the system meeting the acceptance criterion.

The **VT** process involved in Figure 19 is mainly conducted by numerical analysis rather than practical experiment; therefore, this process can be termed as **Virtual Testing (VT)**, i.e. using **R-analysis** to predict system response from **DM** instead of **R-test.** Engineer does not need to practically work out the real structure for testing; therefore, **VT** can largely reduce the cost and time of trial-and-error effort in comparison to **Real Testing**.

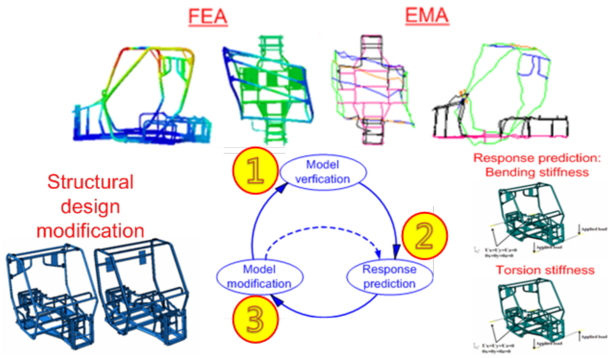


Figure 21: Virtual Testing (VT) processes for UV frame structure design.

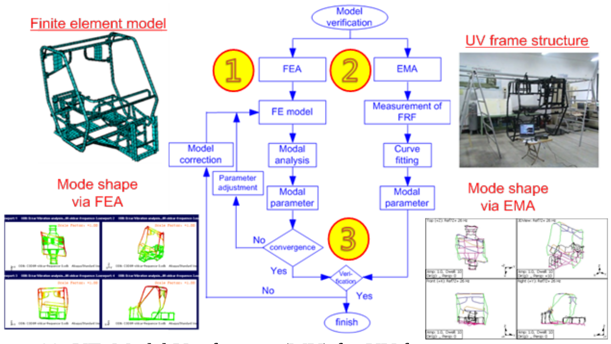


Figure 22: VT: Model Verification (MV) for UV frame structure.

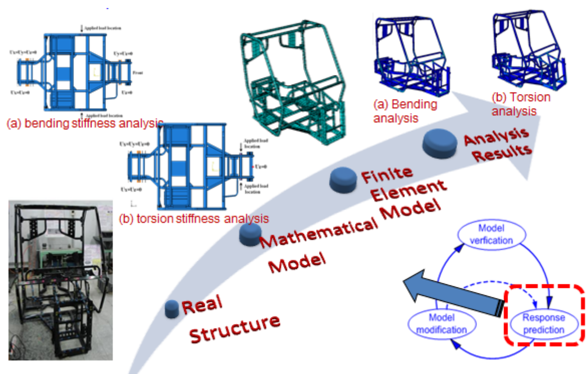


Figure 23: VT: Response Prediction (RP) for UV frame structure.

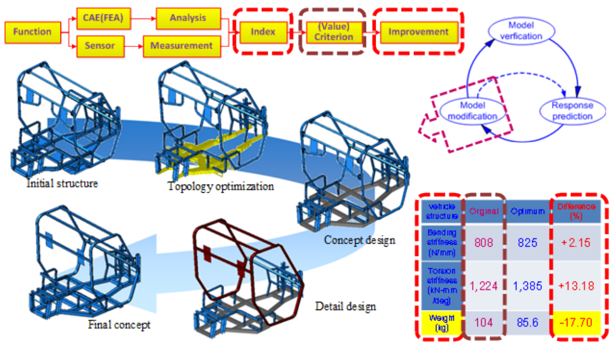


Figure 24: VT: Design Modification (DM) for UV frame structure.

Figure 21 shows **Virtual Testing** (**VT**) processes for UV frame structure design to reduce the weight but maintain the sufficient structural stiffness [16]. There have three steps, i.e. **MV**, **RP** and **DV**. Figure 22 reveals the details of **MV** process, including both numerical simulation for theoretical modal analysis (**TMA**) by FEA and experimental modal analysis (**EMA**). The UV frame's modal parameters obtained from FEA and EMA are compared, and the FE model is updated with satisfactory equivalent modal properties; therefore, the FE model can be calibrated to be equivalent to the practical structure. Figure 23 shows the **RP** process for determining the structural stiffness, in terms of bending and torsional stiffness of the UV frame structure. Both bending and torsional stiffness are the evaluation indices for lightweight design analysis. Figure 24 shows the **DM** process in performing structural geometry modification to reduce the structural weight but maintain at least the same stiffness or higher. Results show the weight of frame structure is reduced by 17%, while the bending stiffness and torsional stiffness are increased by 2% and 13%, respectively.

5. NVH DIAGNOSIS APPROACH

Section 4 conveys the systematic procedures in product design process by numerical or experimental approaches; however, there is always some unexpected condition of product fault, e.g. NVH is exceeding the acceptance criterion. During the product design and manufacture process, the most challenge work is probably to **diagnosis the NVH problems** of product and **come out with proper solution**. Since the design can hardly achieve the goals free from N&V at the first attempt, to investigate the N&V problem and get the improvement need "**feedback**" and "**solution**" skills. Before carrying on the N&V diagnosis, engineer should know better about his **accessibility** for tools including software and hardware and his **ability** on numerical analysis and experimental work. The main objective to diagnosis the product fault is to **feedback the information** of fault product and **selects the solution** to prevent the fault. Figure 25 layouts the big picture for consideration of NVH diagnosis and improvement. Discussions are as follows:

1. **Top level**: the first step is to define **Function**, i.e. the purpose of NVH project. Engineer needs to think about "**why**?" and "**what goals**?" to solve the NVH problems so as to define his NVH project appropriately.
2. **Approach method**: there always have two options, i.e. analytical/numerical and experimental approaches or applying both, respectively, to carry out the NVH project. The procedures are "**FCAICI**" and "**FSMICI**" as discussed in **Section 4**.
3. **On-going level**: there are three steps to follow essentially.
   (1) **Know-what**: engineer must build his abilities to utilize his best accessibility on the tools including software and hardware, and do his best to investigate all the possible conditions for NVH concerns. CAE software and analysis skills are important "**know-what**" tools, while NVH sensors, FFT analyzer and so on are the experimental "**know-what**" tools. The "**know-what**" tools are to **feedback** the NVH condition of product. This is the "**know-what**" stage to realize the target product condition.
   (2) **Know-why**: after the observation on the feedback experimental data or simulation results, engineer's responsibility is to figure out "why", such as what the phenomenon is, what causes the situation, and what possible solutions can be taken to cure the NVH problems. This is the "**know-why**" stage to figure out the reason behind the "**know-how**" action in the next stage.
   (3) **Know-how**: when engineer comes up with a possible improvement action, the major task is to work it out by either **real testing** or **virtual testing** (**VT**) to prove the "**know-how**" is the proper **solution**.

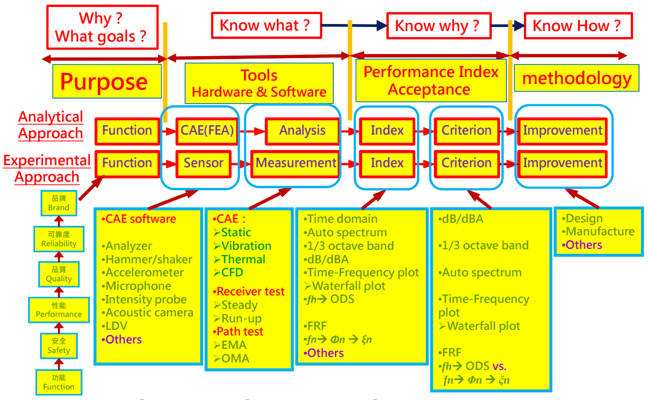


Figure 25: NVH diagnosis and improvement base on “FSMICI” & “FCAICI” Procedures.

In summary, “**know why**”, “**know what goals**” and “**know how to do**” are the tips for top level planning, while “**know-what**”, “**know-why**” and “**know-how**” are on-going level’s tips. It is noted that “**know-why**” is far more important than “**know-how**”. The above mentioned steps and considerations seem easy to carry on; however, there involves much background knowledge, including NVH fundamental knowledge and vehicle engineering domain knowledge. In this work, **Section 3** briefly introduces N&V fundamentals, and **Section 4** shows the general approach about product development. The domain knowledge regarding vehicle engineering is not possible to cover all in this work. Nevertheless, this section will propose a systematic procedure to go on NVH diagnosis for engineer to follow.

When engineer were assigned a task to solve the NVH problem, the **basic procedures** can be as follows:

1. **Define** the project.
2. Think “**why**” and “**what goals**”.
3. Plan “**how to do**”.
4. Carry on diagnosis to **feedback** information and find **solution**.
5. **Report** solution and results.

First, engineer should be able to **define** his project title clearly and **think** about “**why to do this project**?” and “**what goals for this project**?” Then, engineer can work out his **plan** about “**how to do this project**”. No matter what the plan, engineer definitely needs to **carry on** his diagnosis work until the problem solved. Finally, to **report** is important step so as to close the project.

The **NVH diagnosis procedure** may involve many experience-oriented actions; however, some basic steps for “**how to do**” can be suggested as follows [17]:

1. **Perform R-test**. The first step is to know the **N&V situation** of target at **complaint operating condition**. Other than the specified condition, the target can be investigated in **steady state** running condition as well as the **run-up** or **coast-down** test. The correlation between **N&V** can be examined to make a good guess on the problem base on the evidence of test results.
2. **Perform P-test (EMA)**. From the **R-test** results for **N&V**, engineer can start the **P-test** on the most possible cause of the structure, and so on. **P-test** on the **air-path** is also the possible alternative option.
3. **Compare the results from R-test and P-test**. The tip in the comparison process is to gather those **indices** obtained from **R-test** and **P-test**. At this stage, engineer could possibly identify the cause of NVH either from the **source** or from the **path**.
4. **Seek for design modification (DM)**. Solutions for improvement of NVH can be multiple choices. The tip for seeking solutions is **SPR**, such as source **isolation**, path **separation**, receiver **insulation**, **modification** on source and path, etc. The tip for **DM** is regarding to **GMBI** or **MCK**. **GMBI** has been discussed in **Section 3**. **MCK** stands for mass, damping and stiffness. Engineer needs to apply his NVH techniques either by numerical simulation such as **VT** or experimental testing to feedback the information about the status of modified product and to prove the solution effecitve.
5. **Repeat above steps**. The **solution** is based on what information you can **feedback**, and **information** comes from those **data** that you can interpret. What can be **feedback** depends on what **solution** skills you have, i.e. what **tools** you have and what numerical and experimental **abilities** you can. To **diagnosis** and come up with the effective **DM**, engineer needs to train having sufficient **feedback** and **solution** skills, i.e. the spirits of Industry 4.0: **IoT** and **CPS**.

Figure 26 summarizes the application of above **NVH diagnosis procedure** to treat the wiper noise problem. Both **R-test** and **P-test** are conducted, respectively, to **know what** the N&V situation of wiper system. CAE software can be applied to carry out **P-analysis** to assist to **know why** the structural vibration characteristics, and so forth the source and path of wiper noise can be possibly identified. Then, the appropriate solution can be proposed to **know how** to improve the N&V problem.

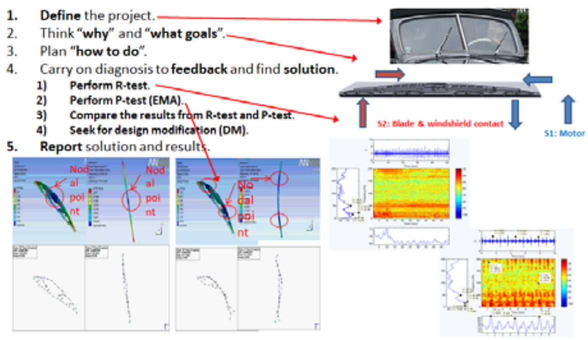


Figure 26: Application of NVH diagnosis procedure to wiper noise improvement.

6. Conclusions and Recommendations

This work presents the general topics about **N&V** and introduces **the spirits of Industry 4.0**, i.e. **feedback** and **solution**, related to NVH concerns in vehicle engineering. The intention of this work is to provide the fundamentals of **N&V knowledge** for engineers and propose the systematic steps in product development and improvement, i.e. “**FCAICI**” for numerical approach and “**FSMICI**” for experimental approach. The concept and practical application of **Virtual Testing** (**VT**) for product development in contrast to real testing are also illustrated for the case study of vehicle lightweight design by carrying out **MV**, **RP** and **DM**. Finally, the **NVH diagnosis procedures** are proposed and illustrated by wiper system noise improvement.

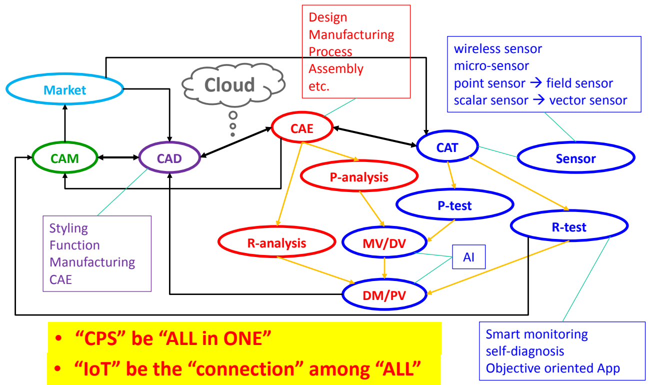


Figure 27: NVH techniques for future development.

To implement **N&V techniques** to vehicle engineering that contain lots of numerical and experimental skills, **engineer** needs to build up his abilities to carry on the NVH project. On the other hand, **manager** is responsible to provide adequate tools including software and hardware facilities for engineers to hand on their work. Figure 27 presents the big picture for future development of NVH techniques implementing the spirits of Industry 4.0. The main themes is summarized that IoT and CPS can be implemented by CAD/CAM/CAE/CAT that is connected to each other as shown in Figure 27 and discussed as follows:

1. **CAD**: all of product design can start from CAD software, and the design goals and detail specifications can come from the **feedback** of market information. The applications of CAD may have different aspects such as **styling** design, **functional** design, **manufacturing**, advanced **analysis** via CAE, etc.
2. **CAE**: Computer Aided Engineering (**CAE**) is simply the technique to simulate the real structure including **P-analysis** and **R-analysis**. The purposes of analysis can be for product design with six different stages as shown in Figure 3 and manufacturing issues in process, assembly, etc.
3. **CAT**: whatever simulation is taken, experimental verification is necessary to make sure the correctness and effectiveness of **CAE**. **CAT** is Computer Aided Testing that contains **P-test** and **R-test** corresponding to **P-analysis** and **R-analysis**. Smart monitoring, self-diagnosis, objective-oriented app, etc. can be the future trend.
4. **MV/DV**: Model Verification (**MV**) requires **P-analysis** and **P-test**, while Design Verification (**DV**) is generally to confirm the design system; therefore, **MV** and **DV** are after **P-analysis** and **P-test**.
5. **DM/PV**: Design Modification (**DM**) generally involves **R-analysis** and **R-test**, and so does Product Validation (**PV**). Artificial Intelligence (**AI**) techniques may be implemented to expedite the MV/DV/DM/PV process.
6. **CAM**: Computer Aided Manufacturing (**CAM**) is just the simple term here for manufacture that may need CNC machine tools, robot assisted work, automated assembly, smart and flexible manufacturing, etc.
7. **Market**: products are for sale in the market. There must have the mechanism to **feedback** market information regarding consumer's opinions. So, the sensing techniques, such as wireless sensor, micro-sensor, point sensor to field sensor, scalar sensor to vector sensor, etc., are crucial for feedback.

Figure 27 can be summarized as the followings in terms of **spirits of Industry 4.0**:

1. **"CPS" be "ALL in ONE."** Each block in Figure 27 can be considered a cell of CPS element, and all of CPS elements can also be integrated in one CPS.
2. **"IoT" be the "connection" among "ALL."** IoT is to make the "connection" among all cells of CPS. The Cloud technique and environment are then created to link all CPS elements together.

Acknowledgments: The author thanks to the financial support of this work by Ministry of Science and Technology under the grant No.: MOST 106-2622-8-020-003 -TE3.

References and Notes

1. Babisch, W., "Transportation Noise and Cardiovascular Risk: Updated Review and Synthesis of Epidemiological Studies Indicate That the Evidence Has Increased," *Noise and Health*, Vol. 8, No. 30, pp. 1-29. **(2006)**
2. Campillo-Davo, N., and Rassili, A. (eds.), NVH Analysis Techniques for Design and Optimization of Hybrid and Electric Vehicles, Shaker Verlag GmbH, Aschen, Germany. http://www.cost.eu/COST_Actions/tud/TU1105 **(2016)**
3. Panza, M. A., "A Review of Experimental Techniques for NVH Analysis on a Commercial Vehicle," *Energy Procedia*, Vol. 82, pp. 1017-1023. **(2015)**
4. Van de Ponseele, P., Van der Auweraer, H., and Janssens, K., "Source-Transfer-Receiver Approaches: a Review of Methods," *Proceedings of ISMA2012*, Leuven, Belgium, pp. 3645- 3658. **(2012)**
5. Cerrato, G., and Goodes, P., "Practical Approaches to Solving Noise and Vibration Problems," *Sound and Vibration*, April, pp. 18-22. **(2011)**
6. COST Action TUD 1105 Year 1 WG1 Task, *Extended Scientific Report: State of art in NVH of ICE and Electrified Vehicles*. **(2012)**
7. Wang, B. T., "Application of Analytical and Experimental Techniques to Design Verification and Product Validation Base on Industry 4.0," *2016 Conference on Precision Machinery and Manufacturing Technology-PMMT 2016*, Pingtung, pp. K001-1~K001-8. **(2016)** (in Chinese)
8. Executive Yuan, *Development Proposal for Productivity 4.0 – 2016 to 2024*. **(2015)** (in Chinese) (www.idipc.chcg.gov.tw/fdown.php?nid=202&fid=1, accessed on 2016/ 04/01)
9. http://rvantage.net/internet-of-things-smart-manufacturing-the-era-of-industry4-0/ (accessed on 2016/ 04/01)
10. https://en.wikipedia.org/wiki/Federal_Motor_Vehicle_Safety_Standards, accessed on 2017/ 03/01.
11. Wang, B. T., Huang, C. H., Wu, Y. H., "Vibro-Acoustic Coupling Analysis for Harmonic Sound Plate," *The 23rd International Congress on Sound and Vibration (ICSV23)*, Athens, Greece, Paper No.:440. **(2016)**
12. Wang, B. T., "Vibration Analysis of a Continuous System Subject to Generic Forms of Actuation Forces and Sensing Devices," *Journal of Sound and Vibration*, Vol. 319, pp. 1222–1251. **(2009)**
13. Wang, B.T., and Lee, Y. C., "Discussions on Vibration Modal Analysis and Sound Radiation of Track Wheel," Measurement Information, Vol. 170, pp. 6-12. **(2016)** (in Chinese)
14. Wang, B. T., Chao, T. C., and Hsieh, M. H., *Manufacturing Method for a Metalophone with a Chord Shape and a Chord Plate of Metalophones*, Taiwan Patent No. I 409801. **(2016)**
15. Wang, B. T., Chao, T. C., and Hsieh, M. H., *Chord Plate Structure of Metalophones*, Taiwan Patent No. I 515718. **(2016)**
16. Wang, B. T., Chen, Y. C., Huang, H. H., and Chen, Y. C., "Model Verification and Structural Stiffness Evaluation for Utility Vehicle Frame Structure," *The 25th World Battery Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition*, Shenzhen, Paper No.: K57HGP01. **(2010)**
17. Wang, B. T., Wang, W. J., Wang, T. W., and Huang, C. S., "Machinery Noise Measurement and Diagnosis Procedure: Application to Twin Screw Compressor," *The 21th National Conference on Sound and Vibration*, Taipei, Paper No. ：A0011. **(2013)** (In Chinese)