The study of problem solving by TRIZ and Taguchi methodology in automobile muffler designation

Tzann-Dwo Wu
Assistant Professor, Department of Industrial Management, Tung-Nan Institute of Technology
Taipei, 222, Taiwan

Abstract

Deming developed a new quality-improving concept, which extended quality inspection to statistic process control (SPC). Taguchi is further to improve quality techniques by production step to trace back to the design phase. Design phase then so-called off-line quality control, is to point the source principal superintendence, introduce quality into "product and manufacturing processes design phase", can reduce the cost and stilted qualities significantly. The activities of off-line quality control are promoted by Design of Experiments (DOE), the best products and manufacturing process in strike out (i.e., engineering optimization). This study is guide "TRIZ theory and Taguchi methods" in automobile muffler design phase to fit the requirements of "engineering optimization designs. For practical accreditation in muffler designation, the process of problem solving by TRIZ and Taguchi method and the procedure of applying Taguchi method to parameter and tolerance design were established. Base on BEM, characteristics and performance analysis of noise reduction and transmission loss and "80-20 Rule", we got priority for automobile muffler designation: 1st. Dual-perforated intruding tube muffler; 2nd. Simple expansion with dual ¼ L intruding tube chamber; 3rd Dual-Perforated intruding plug tube muffler.

Keyword: TRIZ, concept design, system design, parameter design, tolerance design, engineering parameter, improving parameter, avoiding degeneration parameter, contradiction matrix, Taguchi method, noise factor, quality loss function, orthogonal array, SN, response graph, 2 stage optimization procedure, optimized combination, muffler, transmission loss

1. Introduction

Deming developed a new quality-improving concept, which extended quality inspection (on-line quality control) to statistic process control (SPC). Taguchi is further to improve quality techniques by production step to trace back to the design phase. Design phase then so-called off-line quality control, is to point the source principal superintendence, introduce quality into "product and manufacturing processes design phase", can reduce the cost and stilted qualities significantly. The activities of off-line quality control are promoted by Design of Experiments (DOE) [2, 3], the best products and manufacturing process in strike out (i.e., engineering optimization). And the design phase has four: (1) conceptual design; (2) system design; (3) parameter design; (4) tolerance design. This study applied "TRIZ theory and Taguchi methods" in automobile muffler design phase (as shown in Table 1.) to fit the requirements of "engineering optimization designs" (its process detailed as Figure 1).

1. Concept Design （C/D）

   Design engineer try to find more efficient "quality loss function" (e.g., low sensitivity and small noise factor) by utilizing innovation, invention, creativity, QFD, Kano Model[5], brainstorming techniques. To stimulate new concepts happened, create prototype and product and finally select the optimum alternative by trial and error method.

2. System Design (S/D)

   While designing and developing products or service should consider its basic function, performance, VOC and latency risks. Also steer the input and output of the correlation request and designation [1], as the Table 2.

3. Parameter Design (P/D)

   P/D has the same meaning with Robust Design (R/D); minimize quality losses in products or in the manufacturing process (i. e., N/F Sensitivity), make quality reaction value (y_i) to meet target value (y_m).

   ・Min（N/F Sensitivity）→ Min（Quality Loss）

   – Reduce the cost of manufacturing or quality loss (QL) (replace by lower class kit/material).

   – Deciding the best combination of parameters.

4. Tolerance Design （T/D）

   ・Reduce QL that performances of product change caused.

   ・Reinforce cost of manufacture, discreetly choose the high class material factor of reducing the tolerance.

Table 1. 4 Phases in Product Design

Phase	Methodology	Application
1^{st}. Concept Design 2^{nd}. System Design	TRIZ Theory	• Innovation • Invention • Trial & Error • Better Design
3^{rd}. Parameter Design 4^{th}. Tolerance Design	Taguchi Method	• 2 Stage Optimization Procedure — 1^{st} : Reduce variance by P/D — 2^{nd} : Adjust accuracy ($\bar{y} \rightarrow y_m$) by T/D • DOE • Quality Engineering • Robust Design (R/D)

Table 2. Related information's input and output for System Design

Input	Output
1. Functional and Performance requirements 2. Applicable statutory and regulatory requirements 3. Information derived from pervious similar design 4. Requirements shall be complete and unambiguous.	1. Meet the input requirements for design and development. 2. Contain or reference product or service acceptance criteria/standard. 3. Specify the characteristics of the product or service that are essential for its safe and proper use.

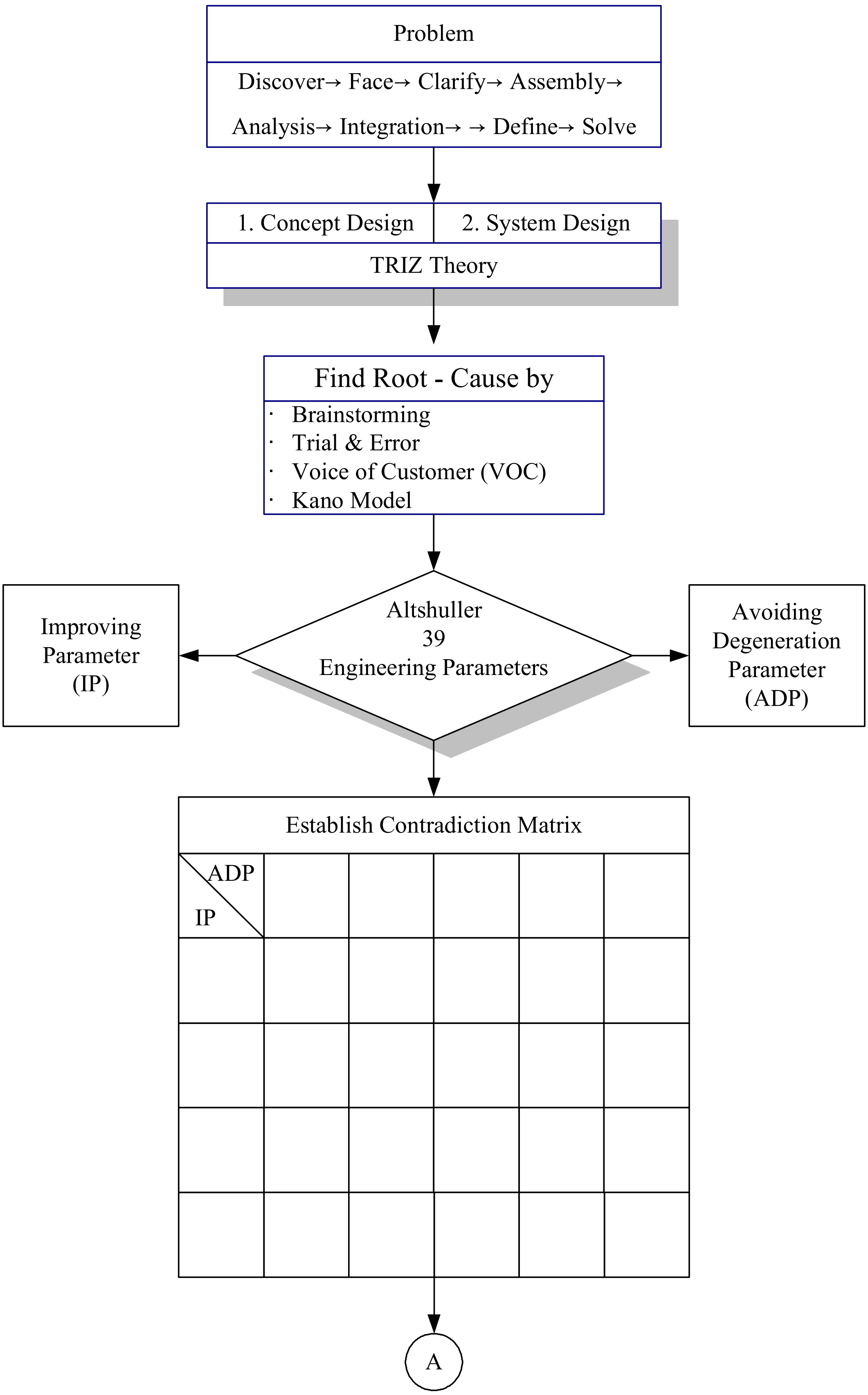


Figure 1. Process of Problem Solving by TRIZ and Taguchi Methodology in Automobile Muffler Designation-1

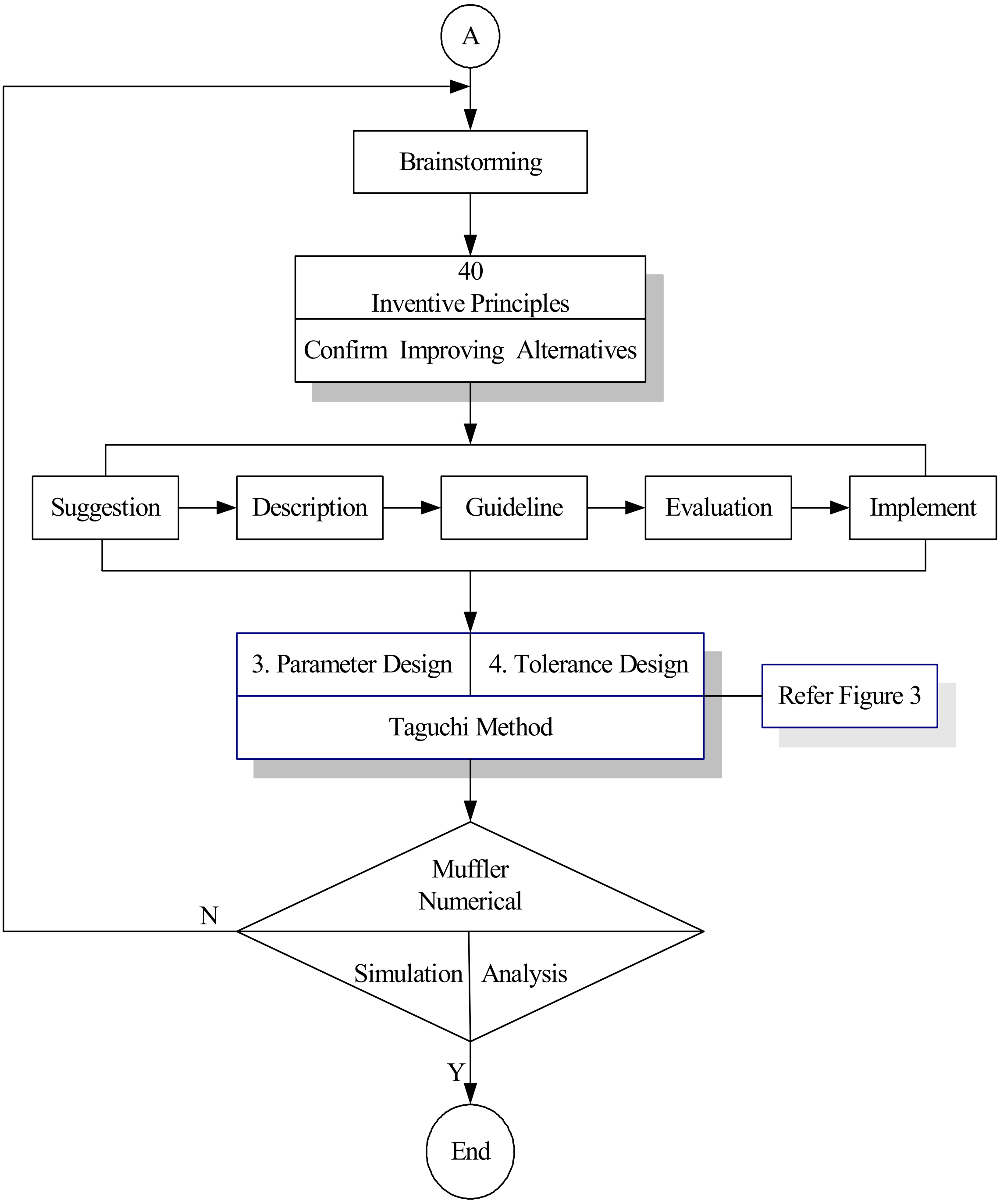


Figure 1. Process of Problem Solving by TRIZ and Taguchi Methodology in Automobile Muffler Designation-2

2. TRIZ Theory

TRIZ (Teoriya Resheniya Izobretatelskikh Zadatch) theory [4] was created by Russia inventor-Genrish S. Altshuller and its research fellows in 1946. They have analyzed and integrated 1,500,000 patents since 50 years ago. Also assume "universe exists an universal inventive principle, it's a base of innovation, invention and creativity for new techniques", and detects two phenomena: (1) exist a basic and common question and its problem solving models for the different creative invention questions; (2) the same problem solving alternative can multiplicity uses in resolve the problems that corresponding different period, different province station come. TRIZ definition for: (1) Theory of Inventive Problem Solving (TIPS) and tool; (2) have the cerebration and problem solving models (as Figure 2.) of the systematic, repeatability, reliability [4]; (3) TRIZ 40 principles versus 39x39 rank engineering parameters matrix ($P_{improving} \times P_{Avoiding\ Degeneration}$) (i.e., conflict matrix), to solve the engineering conflict, technology contradiction and promote quality and efficiency.

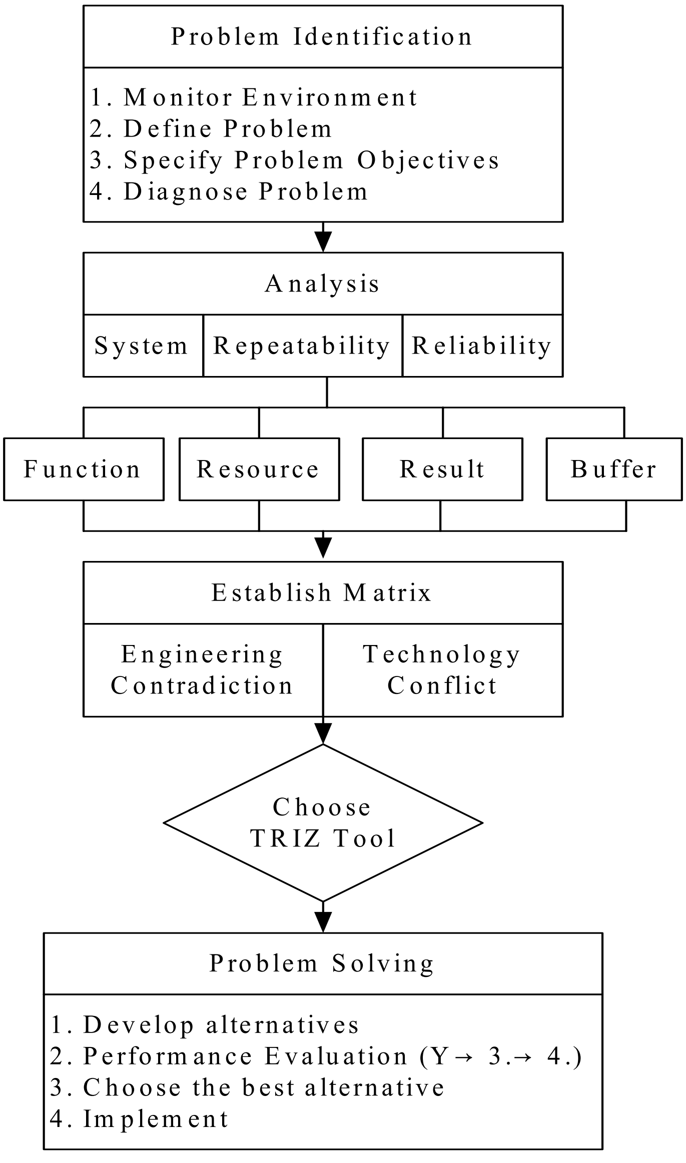


Figure 2. TRIZ Thinking Model for problem solving

2.1 Technology System

Any article can run certain kind of function, call it “technology system”. And the technology system can be constituted by one or several subsystems, and its hierarchy organization also has two subsystem of the components at least. When the technology system generates badly function or don’t have the expectancy function, then have to improve it. Generally, the systematic facilitation really can’t be well timed by the trial and error method and accurate to find out root-causes.

2.2 Technology Contradiction

When improving certain a parameter attribute for system, will come another a parameter characteristic deterioration, the technology contradiction that call. The former is an Improving Parameter (IP), the latter then calls the Avoiding Degeneration Parameter (ADP). Altshuller summarized 39 kinds of engineering characteristic parameters from 1,500,000 patents database (as Table 3.) and 40 inventive principles (as Table 4.). When the technique system arises problem, the project team can screen IP and ADP by brainstorming and create “conflict matrix” (as Table 5.), find out the accommodation inventive principles or solutions from Altshuller conflict table subsequently, then proceeding concept design and system design for automobile muffler (as Table 6, 7.).

Table 3. Altshuller 39 Engineering Parameters

1.	Weight of moving object	21.	Power
2.	Weight of stationary object	22.	Loss of Energy
3.	Length of moving object	23.	Loss of Substance
4.	Length of stationary object	24.	Loss of Information
5.	Area of moving object	25.	Loss of Time
6.	Area of stationary object	26.	Quantity of substance /the matter
7.	Volume of moving object	27.	Reliability
8.	Volume of stationary object	28.	Measurement accuracy
9.	Speed	29.	Manufacturing precision
10.	Force	30.	External harm affects the object
11.	Stress/Pressure	31.	Object-generated harmful factors
12.	Shape	32.	Ease of manufacture
13.	Stability of the object’s composition	33.	Ease of operation
14.	Strength	34.	Ease of repair
15.	Duration of action by a moving object	35.	Adaptability / Versatility
16.	Duration of action by a stationary object	36.	Device complexity
17.	Temperature	37.	Difficulty of detecting and measuring
18.	Illumination intensity	38.	Extent of automation
19.	Use of energy by moving object	39.	Productivity
20.	Use of energy by stationary object		

Table 4. TRIZ 40 Inventive Principles

1.	Segmentation	21.	Skipping
2.	Taking out	22.	Blessing in Disguise
3.	Local Quality	23.	Feedback
4.	Asymmetry	24.	Intermediary
5.	Merging	25.	Self-service
6.	Universality	26.	Coping
7.	Nested Doll	27.	Cheap Short-Living Object
8.	Anti-Weight	28.	Mechanics Substitution
9.	Preliminary Anti-Action	29.	Pneumatics and Hydraulics
10.	Preliminary Action	30.	Flexible Shells and Thin Films
11.	Beforehand Cushioning	31.	Porous Materials
12.	Equipotentiality	32.	Color Changes
13.	The Other Way Round	33.	Homogeneity
14.	Spheroidality-Curvature	34.	Discarding and Recovering
15.	Dynamics	35.	Parameter Changes
16.	Partial/Excessive Actions	36.	Phase Transitions
17.	Another Dimension	37.	Thermal Expansion
18.	Mechanical Vibration	38.	Strong Oxidants
19.	Periodic Action	39.	Inert Atmosphere
20.	Continuity of Useful Action	40.	Composite Structures

Table 5. Altshuller Conflict Matrix

② ADP / ① IP		1.	2.	3.	………………	10.	………………	39.
1.								
2.								
3.							③	
⋮								
39.								

①：IP　：Improving Parameter

②：ADP：Avoiding Degeneration Parameter

③：Inventive Principles（#1, 27, 28, 29）

Table 6. Altshuller Conflict Matrix for Automobile Muffler Designation

IP \ ADP	11	13	16	20	23	36
4	1, 14, 35	35, 37, 39	1, 35, 40	—	10, 24, 28, 35	1, 26
6	10, 15, 36, 37	2, 38	2, 10, 19, 30	—	10, 14, 18, 39	1, 18, 36
8	24, 35	28, 34 35, 40	34, 35, 38	—	10, 34, 35, 39	1, 31
9	6, 18, 38, 40	1, 18, 28, 33	—	—	10, 13, 28, 38	4, 10, 28, 34
10	11, 18, 21	10, 21, 35	—	1, 16, 36, 37	5, 8, 35, 40	10, 18, 26, 35
12	10, 14, 15, 34	1, 4, 18, 33	—	—	3, 5, 29, 35	1, 16, 28, 29
27	10, 19, 24, 35	—	6, 27, 34, 40	23, 36	10, 29, 35, 39	1, 13, 35
28	6, 28, 32	13, 32, 35	10, 24, 26	—	10,16, 28, 31	10, 27, 34, 35

Table 7. Technology Contradiction and Inventive Principles Table for Automobile Muffler Designation

Problem Description	Improving Parameter	Avoiding Degeneration Parameter	Inventive Principles
1. Reduce Noise of Vehicle’s Muffler 2. Improving Muffler Transmission Loss 3. Simply Muffler Designation 4. Absorbent Material be used	4. Length of Stationary object 6. Area of Stationary object 9. Speed 10. Shape	11. Pressure 23. Loss of Substance	1. Segmentation 5. Merging 10. Preliminary Action 13. Invert Action 14. Spheroidality 18. Mechanical Vibration 28. Mechanics Substitution 31. Porous Materials 35. Parameter Changes 36. Phase Transitions

3. Taguchi Method

3.1 Noise Factor（N/F）

Product at the practice use, its quality characteristic or response value result from product function change, target value drift and quality loss because some rhea factors (product, environment, time). Its type has four: (1) External Noise: generate dissociation is because of the product praxis environment, bear the burden and transaction methods; (2) Unit- to-Unit Variation: can't avoid on the manufacturing process its dissociation; (3) Deterioration product quality would be recession or inferior by components decade and time rapid growth; (4) Process Noise: includes external to the process, process no uniformity and process drift. Therefore, how to judge by engineering experience, identify and minimize noise factor are good for improving quality loss.

3.2 Quality Loss Function (QLF)

Taguchi recognizes the customer's desire to have products that are more consistent, part-to-part and a producer's desire to make a low-cost product. The loss to society is composed of the costs incurred in the production process as well as the costs encountered during use by the customer (repair, lost business, etc.). [6] Taguchi defined quality as the loss a product causes to society after being shipped, other than any losses caused by its intrinsic functions. [7]. In product life cycle, quality characteristics or response value (y) will deflect from y_m (target value) caused by product, environment, time dissociation (i.e., out of product specification or quality loss). The exact nature of the loss function for every quality characteristic is difficult to determine. Taguchi assumed that losses could be approximated by a quadratic function so that larger deviations from target cause increasingly larger losses. OLF contain four kind types: (1) Nominal-The- Best (NTB); (2) Larger- The- Best (LTB); (3) Smaller- The- Best (STB); (4) Non- Symmetry- Nominal-The- Best (NS-NTB) is shown in Figure 3.

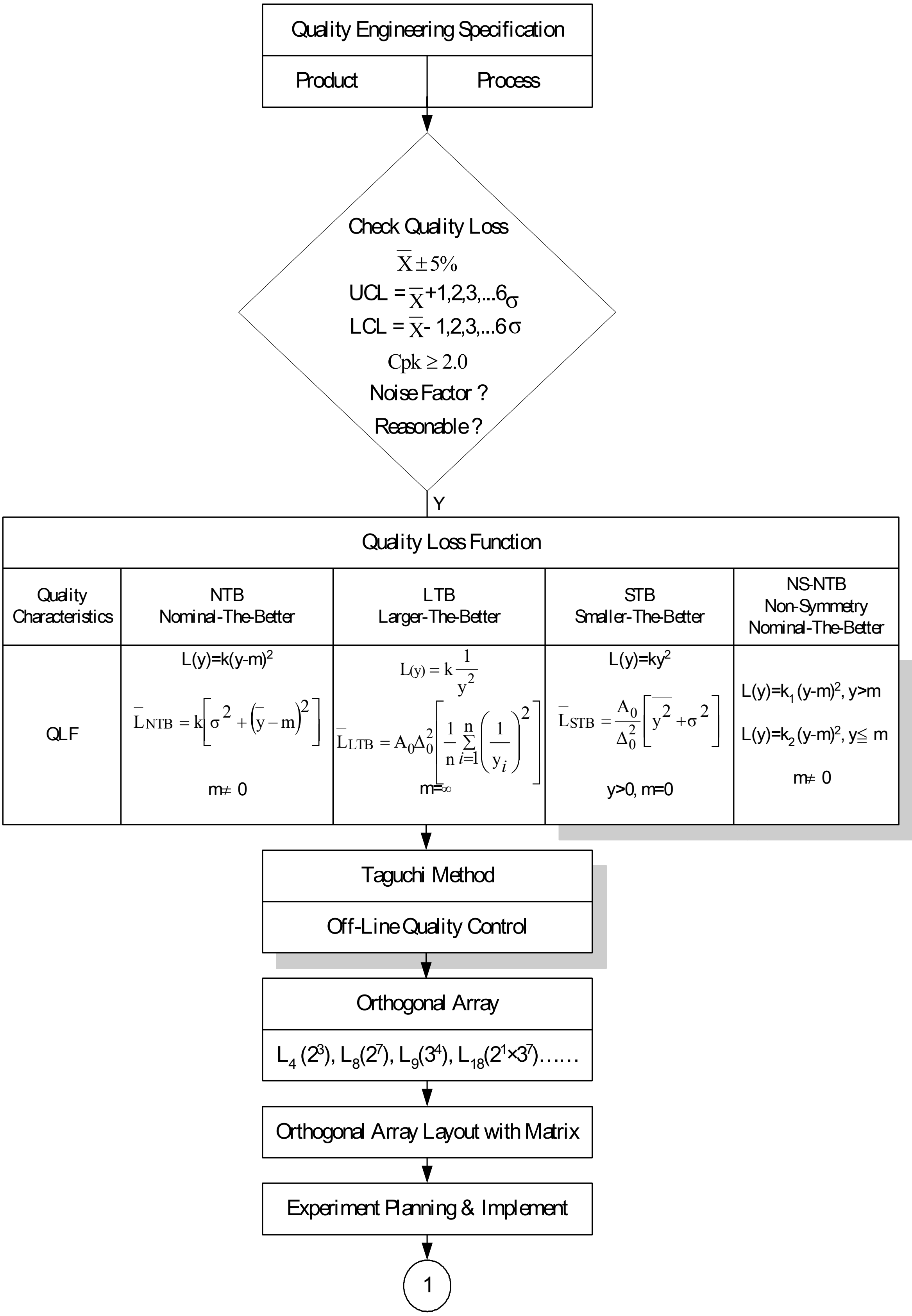


Figure 3-1 Procedure of applying Taguchi method to parameter and tolerance design

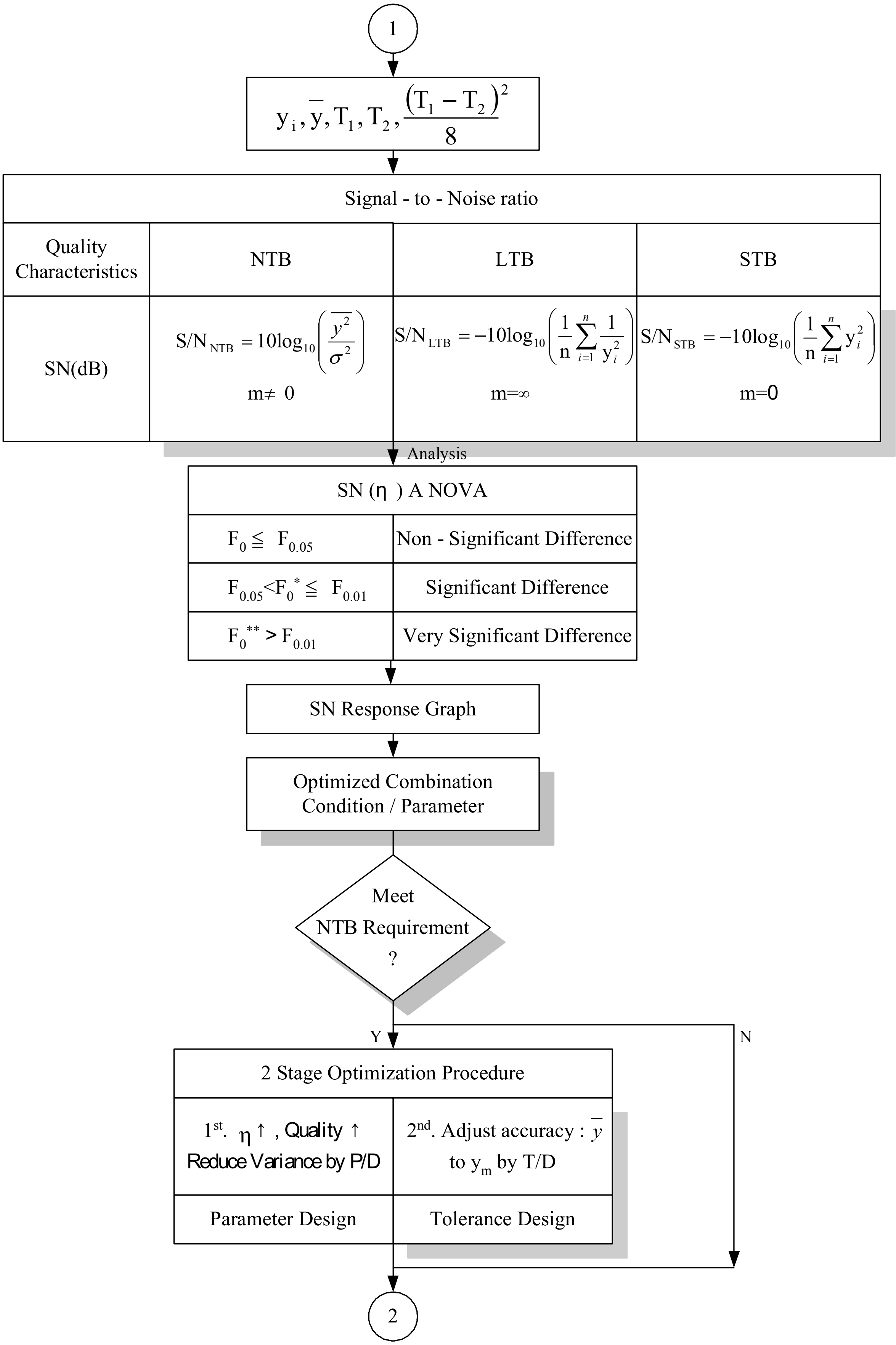


Figure 3-2 Procedure of applying Taguchi method to parameter and tolerance design

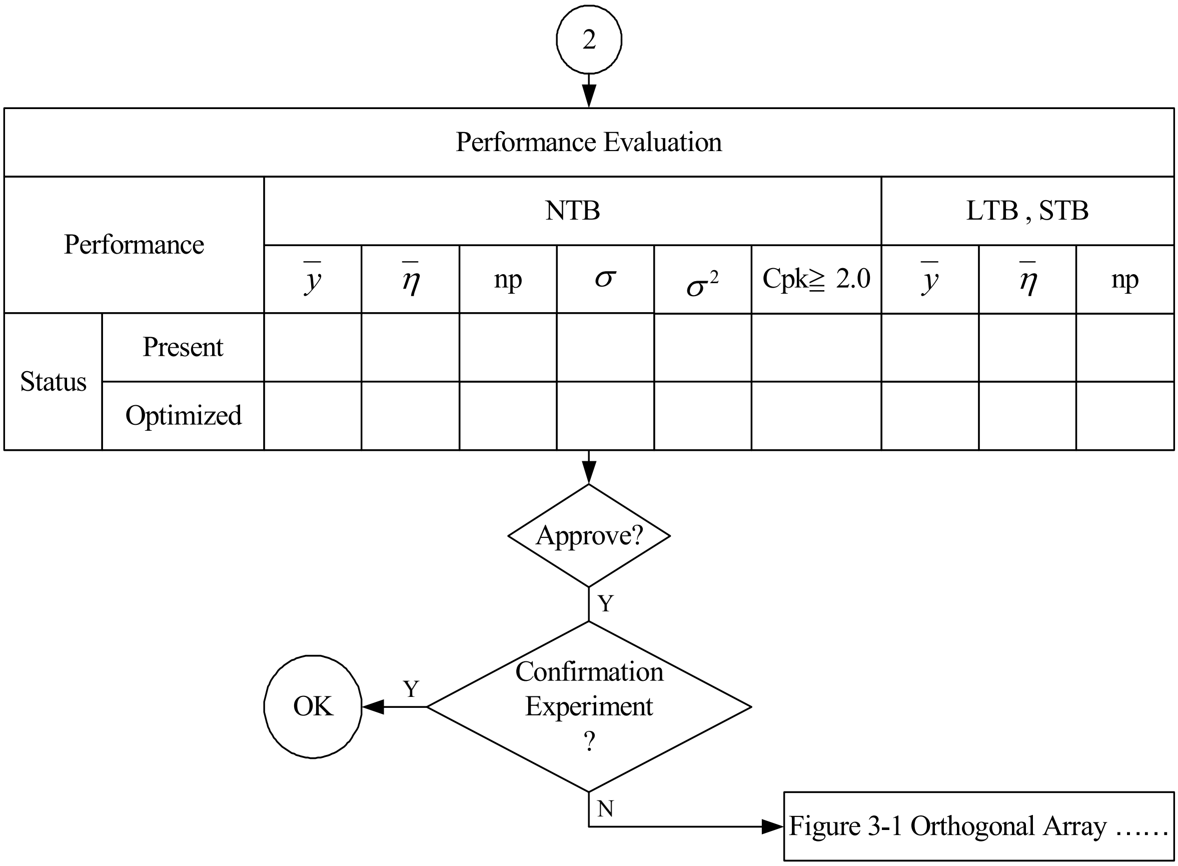
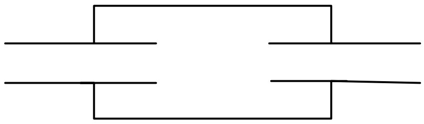
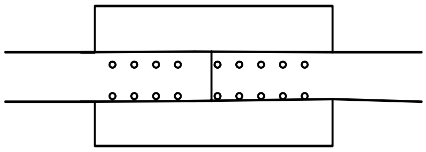
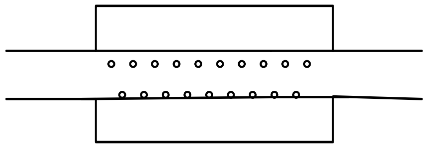
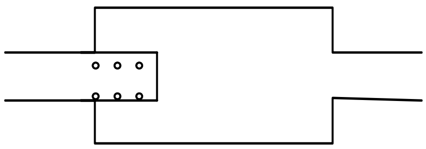
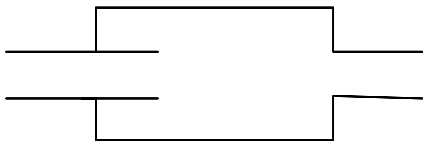
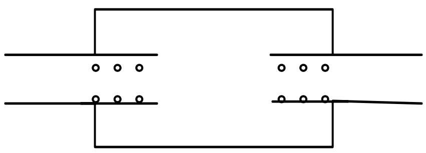
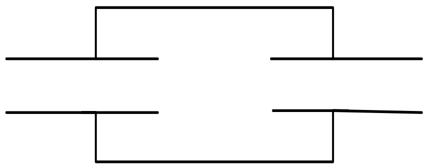


Figure 3-3 Procedure of applying Taguchi method to parameter and tolerance design

3.3 Orthogonal Array Layout

Taguchi is for reducing and simplifying experiment's frequency and treatment, toeing acquires the best factors and effects combination. Orthogonal array are made up of factors and levels, its common usage : $L_4\,(2^3)$, $L_8\,(2^7)$, $L_9\,(3^4)$, $L_{16}\,(2^{15})$, $L_{18}\,(2^1{\times}3^7)$, $L_{27}\,(3^{13})$. In this study , $L_8\,(2^7)$ was used to layout control factors (segmentation, merging, invert action, porous materials) and levels (1, 2) for automobile muffler designation (as Table 8., 9).

Table 8. Control Factor and Level for Automobile Muffler Designation

Factor	Control Factor*	Level (muffler type)	
		1	2
A	Segmentation	Simple expansion w/i dual 1/4L intruding tube chamber 	Simple expansion chamber 
B	Merging	Dual-Perforated intruding plug tube muffler 	Straight-through resonator 
C	Invert Action	Single-Perforated intruding plug tube muffler 	Simple expansion w/i single 1/4L intruding tube chamber 
D	Porous Materials	Dual-Perforated intruding tube muffler 	Simple expansion w/i dual 1/4L intruding tube chamber 

*: Selected by TRIZ 40 Inventive Principles and Table 7. Technology Contradiction and Inventive Principles Table for Automobile Muffler Designation.

Table 9.Experiment Factors Combination for Automobile Muffler Designation - $L_8(2^7)$

$L_8(2^7)$	A	B	A*B	C	e	e	D	$\overline{y_i}$	S/N
	1	2	3	4	5	6	7		
1	1	1	1	1	1	1	1	20	-26.02
2	1	1	1	2	2	2	2	32	-30.10
3	1	2	2	1	1	2	2	38	-31.60
4	1	2	2	2	2	1	1	35	-30.88
5	2	1	2	1	2	1	2	34	-30.63
6	2	1	2	2	1	2	1	31	-29.83
7	2	2	1	1	2	2	1	25	-27.96
8	2	2	1	2	1	1	2	37	-31.36
T_1	-118.60	-116.58	-115.44	-116.21	-118.81	-118.89	-114.69		
T_2	-119.78	-121.80	-122.94	-122.17	-119.57	-119.49	-123.69		
$(T_1-T_2)^2/8$	0.17	3.41	7.03	4.44	0.07	0.05	10.13		
$\overline{\eta_1}$	-29.65	-29.15	-28.86	-29.05	-29.70	-29.72	-28.67		
$\overline{\eta_2}$	-29.95	-30.32	-30.74	-30.54	-29.89	-29.87	-30.92		
	A_1	B_1		C_1			D_1		

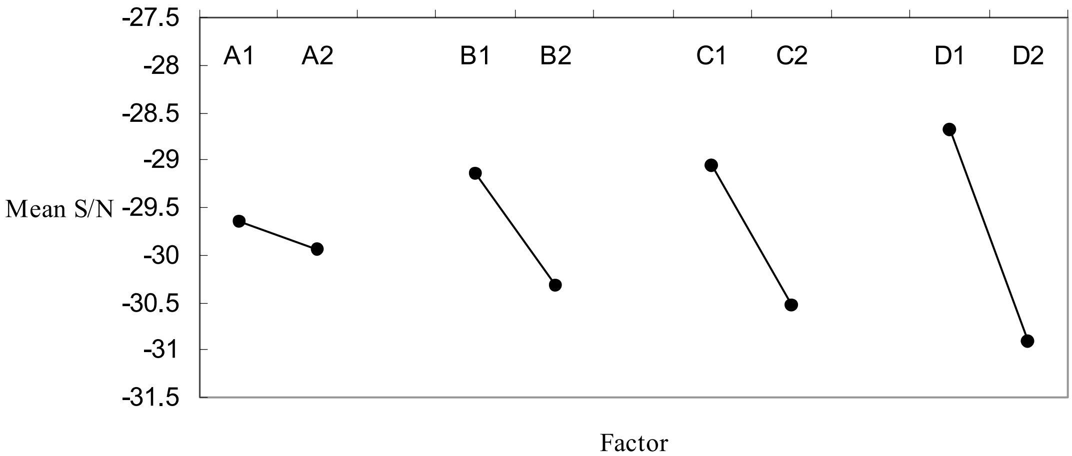


Figure 4. Response Graph

3.4 Signal-to- Noise Ratio (S/N ratio)

Taguchi considers "good quality" should meet: (1) the average value of quality characteristic is in accordance with the target value; (2) the variation of quality characteristic is the smaller the more addicted Taguchi created S/N then can consider the average value and variance simultaneously, and to measure system reliability. When S/N ratio is higher, the product quality is higher, and the quality loss is smaller. Finally choose the highest S/N, and then reorganize the best factor and level combination. S/N contain three types, knowing well as the Figure 3. In this study, we used STB (Smaller-The-Better) to calculate S/N, $\bar{\eta}$, ANOVA and draw response graph for automobile muffler type designation, then get the best combination (A_1 B_1 C_1 D_1) (shown in Figure 4., Table 10.).

Table 10. ANOVA Table

Factor	SS	df	V	F	$F_{0.05}$	$F_{0.01}$
A	0.17	1	0.17	2.83	18.51	98.49
B	3.41	1	3.41	56.83**		
C	4.44	1	4.44	74.00**		
D	10.13	1	10.13	168.83**		
A*B	7.03	1	7.03	117.17**		
e	0.12	2	0.06			
T	25.30	7				

4. Muffler Designation

4.1 Muffler Principles and Theory

The cardinal noise in metropolitan district derives from the motor vehicle exhaustion tail pipe then muffler uses to provide a restraint or controlling function for noise reduction. Muffler divides into two types: (1) reactive muffler: make use of acoustics impedance to reflect sound source; (2) dissipative muffler: transform sound energy to heat by lining absorbed materials.

Dissipative muffler is in using process, the reasons are: (1) the pore of the lining absorbed material jammed; (2) high temperature make material changed in character; and decreased sound restraint effect. It's not available for high temperature and air pollution (CO, HC, NO_x, PM) environment. For this, the special chosen of research strikes "reactive muffler" to progress development and design the optimized combination by TRIZ and Taguchi method.

4.2 Noise Reductions and Transmission Loss

For the theoretical study, we apply BEM (Boundary Element Method) to analyze 8 types of reactive mufflers used in automobile designation (shown in Table 11.). The estimation of TL (Transmission Loss) is based on the same conditions:

1.specification of muffler

- inlet tube diameter
- outlet tube diameter
- tube thickness
- hole diameter

2.mean flow / Mach number

3.mean temperature

4.mean length / diameter/ porosity for perforated intruding tube

4.2.1 Theoretical Formulation

1.Simple expansion chamber

(1) BEM theoretical formulation with deriving process

(2) Calculate TL

(3) Draw characteristics figure with TL (dB)- Frequency (Hz)

2.Simple expansion with single ¼ L intruding tube chamber

3.Simple expansion with dual ¼ L intruding tube chamber

4.Straight – through resonator

5.Single – Perforated intruding tube muffler

6.Dual – Perforated intruding tube muffler

7.Single – Perforated intruding plug tube muffler

8.Dual – Perforated intruding plug tube muffler

4.2.2 BEM formulation:

Sound wave spreads in space, under controlling for sound pressure, its running pattern can be described by wave equation. Suppose sound wave as the harmonic motion, then sound wave motion satisfy Helmholtz equation [8, 9, 10]:

$$\nabla^2 P + k^2 P = 0 \quad \text{(1)}$$

k: wave number

If describe muffler inner deemed to an acoustics space, the sound wave is in the propagation of the muffler inside can be identified by Helmholtz equation. If converse to boundary integral formulation, we can get:

$$C(\bar{x})P(\bar{x}) + \int_{\rho} \frac{\partial u^*(\bar{x},\bar{\xi})}{\partial n \; (\bar{\xi})} \; p(\bar{\xi})\, d\rho(\bar{\xi}) = \int_{\rho} u^*(\bar{x},\bar{\xi}) \frac{2p}{2n}(\bar{\xi}) d\rho(\bar{\xi}) \quad \text{(2)}$$

Where u* $(\bar{x},\bar{\xi})$ is the fundamental solution of Helmholtz equation. C$(\bar{x})$ is an internal solid angle at point $\bar{x}$. If divide boundary into several surfaces for integral, then can obtain the relation of sound pressure with sound pressure gradient for the grid points of surfaces Finally, can immediately solve by reasonable and available condition. There are different structures and compositions in muffler designation. Usually, it can't handle with single acoustic space directly, so need to divide several surfaces by geometric shape or boundary condition separately.

In Table 11, type 1, 2, 3 can directly analyze by single acoustic space, type 5, 7 analyze by dual acoustic space, and type 6, 8 need to partition three zones. Firstly, apply formula (2) to each acoustic space, can get the relationship between sound pressure and pressure gradient (or velocity) respectively. Then, combined an enlarged acoustic space (i.e. muffler chamber) which included inlet and outlet by the same opening pressure and velocity or acoustic impedance condition of perforated intruding tube Finally, can obtain pressure vs. velocity transformation formula between inlet and outlet of muffler [8, 9, 10].

$$\begin{Bmatrix} p_{in} \\ \rho_0 c u_{in} \end{Bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{Bmatrix} p_{out} \\ \rho_0 c u_{out} \end{Bmatrix} \quad \cdots\cdots(3)$$

Where $\begin{bmatrix} A & B \\ C & D \end{bmatrix}$ is four-pole matrix between inlet and outlet of an acoustic system and A, B, C, D are four-pole parameters. Transmission loss of muffler can be expressed as follows [6, 7].

$$TL = 20\ \log_{10}\left|\frac{A+B+C+D}{2}\right| \quad \cdots\cdots(4)$$

4.2.3 Numerical simulation and analysis

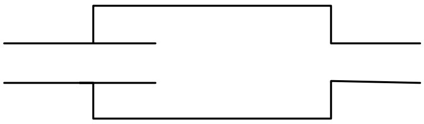
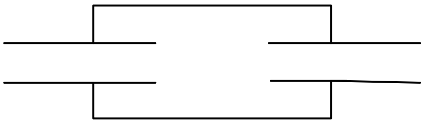
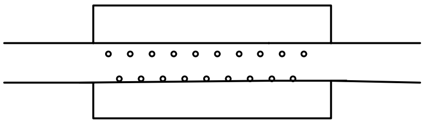
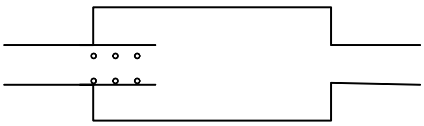
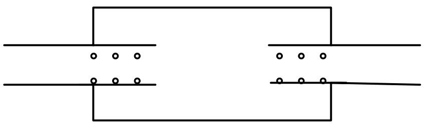
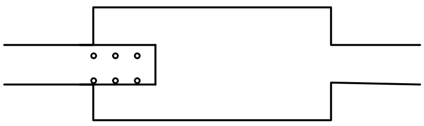
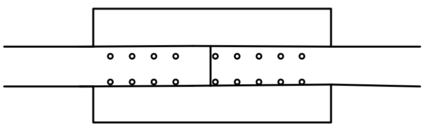
To perform the numerical simulation by formula (4), the related specifications of muffler are identified as follows [11]: (1) expansion chamber length L_c=16cm; (2) expansion chamber radius r_c=6cm; (3) inlet and outlet intruding tube length L_i=4cm; (4) intruding tube diameter R_i=2cm; (5) intruding tube thickness t_i=1mm; (6) drilling hole diameter R_h=2mm; (7) mean flow velocity M=0.1; (8) porosity σ=0.05. Table 11.shows the transmission loss (dB) of 8 types muffler at different frequency. We summarized two states for the optimized designation of muffler: (1) at 1,500Hz-muffler type 8>3>2>7>6>5>1; (2) at 2,500Hz-muffler type 6>3>8>7>5>2>1.Base on characteristics and performance analysis from Figure 5.-8.,"80-20 Rule" and "Benefit and Cost analysis", we got priority for automobile muffler designation:

1st . 6. Dual-perforated intruding tube muffler (D_1)

2nd. 3. Simple expansion with dual ¼ L intruding tube chamber (A_1)

3rd .8. Dual-Perforated intruding plug tube muffler (B_1)

Table 11. Transmission Loss (TL) of 8 Types Mufflers

Muffler Design drawing	TL / Muffler type	Frequency (kHz)									
		0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
	1. Simple expansion chamber	10	20	0	23	0	27	1	0	3	5
	2. Simple expansion with single 1/4L intruding tube chamber	10	25	5	36	12	32	5	6	10	7
	3. Simple expansion with dual 1/4L intruding tube chamber	10	20	5	42	25	40	5	4	14	11
	4. Straight-through resonator	0	2	3	5	16	12	21	0	0	0
	5. Single-Perforated intruding tube muffler	10	27	13	28	21	33	29	11	5	0
	6. Dual- Perforated intruding tube muffler	10	28	15	32	26	35	30	10	5	0
	7. Single-Perforated intruding plug tube muffler	10	29	16	34	23	35	36	46	15	0
	8. Dual- Perforated intruding plug tube muffler	20	32	22	43	32	37	37	49	20	0

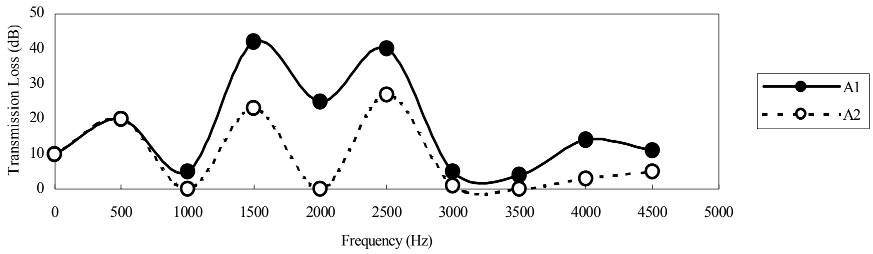


Figure 5. Transmission loss curve-Segmentation: A_1 (Simple expansion w/i dual 1/4L intruding tube chamber) vs. A_2 (Simple expansion chamber)

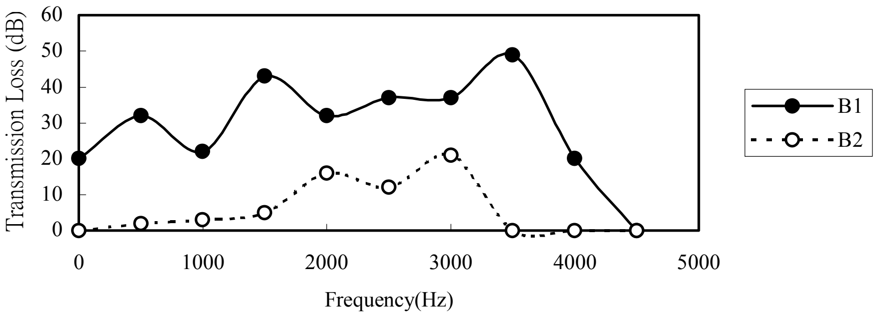


Figure 6. Transmission loss curve-Merging: B_1 (Dual-Perforated intruding plug tube muffler) vs. B_2 (Straight-through resonator)

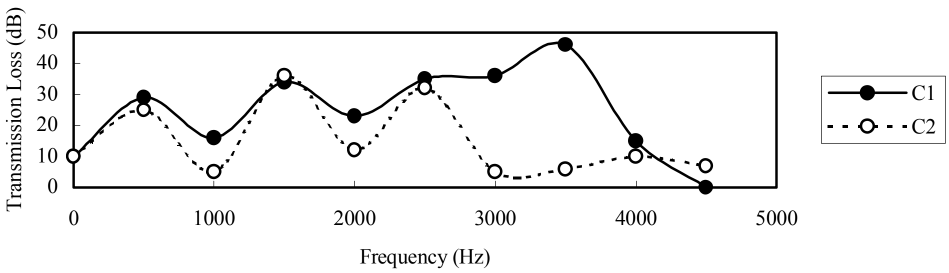


Figure 7. Transmission loss curve-Invert Action: C_1 (Single-Perforated intruding plug tube muffler) vs. C_2 (Simple expansion w/i single 1/4L intruding tube chamber)

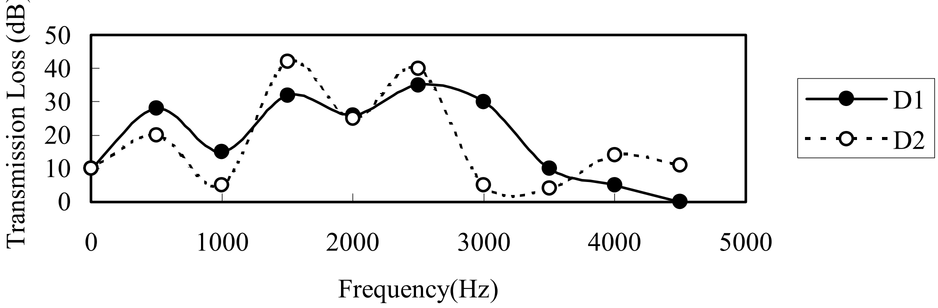


Figure 8. Transmission loss curve-Porous Materials: D_1 (Dual-Perforated intruding tube muffler) vs. D_2 (Simple expansion w/i dual 1/4L intruding tube chamber)

5. Conclusion

In this study, we created a problem solving skill by integrating TRIZ and Taguchi methodology to fit the requirements of "engineering optimization designs". For practical accreditation in muffler designation, the process of problem solving by TRIZ and Taguchi method and the procedure of applying Taguchi method to parameter and tolerance design were established. Base on BEM, characteristics and performance analysis of noise reduction and transmission loss and "80-20 Rule", we got priority for automobile muffler designation: 1st. Dual-perforated intruding tube muffler; 2nd. Simple expansion with dual ¼ L intruding tube chamber; 3rd Dual-Perforated intruding plug tube muffler.

Reference

1. ISO 9001: 2000 Quality Management System – section 7.3.2, 7.3.3, 7.3.5, 7.3.6.
2. C. F. Jeff Wu and Michel Hamada, "Experiments Planning, Analysis, and Parameter Design Optimization," John Wiley & Sons, Inc., 2000, pp.1-17.
3. S. W. Cheng, "Implementation of DOE: Objective, Planning, and Analysis, "Institute of Statistical Science, Academia Silica, 2002.
4. TRIZ Journal, www.triz-journal.com
5. Noriaki Kano, "Successful Business Strategies in Changing Age: Attractive Quality and Its Creation, "Attractive Quality and Six Sigma Seminar, BMG, 2003, pp.24-64.
6. Phillip J. Ross, "Taguchi Techniques for Quality Engineering," McGraw-Hill International Company, Inc., 1996, pp.3-20.
7. James R. Evans, William M. Lindsay, "The Management and Control of Quality," South-Western College Publishing, 1999, pp.399-405.
8. Laurence E. Kinsler, Austin R. Frey, Alan B. Coppens, James V. Sanders, "Fundamentals of Acoustic," John Wiley & Sons Inc.,1982, pp.124-139.
9. C. -N. Wang, C., -Y. Liao, "Boundary Integral Equation Method for Evaluating the Performance of Straight-through Resonator with Mean Flow," Journal of Sound and Vibration 216 (2), 1998, pp.281-294.
10. Chao -Nan Wang, Yih-Nan Chen, Jean Yih Tsai, "The Application of Boundary Element Evaluation on a Silencer in the Presence of a Linear Temperature Gradient," Applied Acoustics, 62, 2001, pp.707-716.
11. Chao -Nan Wang, "A Numerical Analysis for Perforated Muffler Components with Mean Flow," Journal of Vibration and Acoustics, Vol.121, 1999, pp.231-236.