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Active engine sound design

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ABSTRACT: *This study investigates the performance of active engine sound design. The engine is the most important part in vehicles. In an internal combustion vehicle engine, the sound generated by the engine is an important performance and quality measurement, especially in the case of sports cars. The theory involves the optimization method and signal processing. One and more microphones are used to acquire the original engine sound which is used as the input to the controller. The controller calculates the optimal secondary sound using optimization method. After the secondary sound is generated by the controller the secondary and original engine sound are superposed, producing the new desired engine sound. The results show the desired new engine sound could be produced by using the method proposed in this study.*

KEYWORDS-*Active engine sound design, internal combustion, optimization method, signal processing, secondary sound.*

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I.INTRODUCTION

Sound is important characteristics in the perception of a car [1]. The sound produced by an internal combustion engine is important to the customer perception of the vehicle's quality and performance. An engine sound goal was set using a desktop acoustic simulator [2]. The actuator was placed inside the car hood.The flow of gases out of the engine moves through the exhaust and out from the exhaust pipe to the environment. This produces the exhaust noise [3, 4]. A certificated standard of evaluations for exhaust sound qualities showed the correspondence to the physical exhaust sound characteristics [5]. Exhaust sound design is the process of modulating exhaust sound into another exhaust sound involving the addition of sound to produce the desired sound quality [6]. Diesel and gasoline vehicle engines follow a rise in sound frequency during acceleration. This is heard during vehicle acceleration [7, 8].

Early simulation involved in the design and development process for target sound definition under legal requirements and design boundary conditions had been done [9].The active vehicle interior and exterior sound design have become essential in the development of high-quality vehicles [10, 11]. A microphone is used to record the engine sound and then transferred into a controller. The controller calculates the amplifier settings for the final release by the speaker from a secondary source. For this application the variations in engine sound are called active sound design [12]. The first goal of this development was to change the sound to make it easier to set component sound targets [13]. The engine sound represents the vehicles' power, so the quality of the engine sound is very important in the customer's perception of the vehicles performance. Active sound design systems make it possible to take into account various driving conditions to provide sound feedback for drivers and pedestrians. The engine sound is important characteristics in the perception of the vehicle. This system is designed to modulate the original engine sound and change the engine sound. For example, a domestic car engine sound could be modified into sports car engine sound. This principle was originally used to reduce engine noise, and later extended to two car engine sounds superimposed to interact to produce a new engine sound. This design is called active engine sound design. The engine sound signature can feel like a powerful engine of a sports car. The active engine sound system design is essential to any vehicles.

II.METHODS

The principle of active design of engine sound is to use the superposition of the original and secondary sound. A microphone is first used to record the engine sound. The recorded sound is then fed into a controller for calculation. The controller calculates the optimal signal for the secondary sources. This secondary source produces a sound to be superimposed with the original engine sound generating another new engine sound. Fig.

1 shows the block diagram of active engine sound design. In this work the optimization method is used to modulate the engine sound. In general, the optimization problem can be defined as follows [14, 15]:

$$\underset{x}{\textbf{Minimize}}\ f(x)$$
$$\textbf{Subject to}\quad c_i(\boldsymbol{x}) = 0\ \ i = 1, \ldots, m_e$$
$$c_i(\boldsymbol{x}) \leq 0\ \ i = m_e+1, \ldots, m, \qquad (1)$$

where $f(\boldsymbol{x})$ is a nonlinear real scalar function of the optimization parameter vector $\boldsymbol{x} = [x_1, \ldots, x_n]^T$, and $c_i(\boldsymbol{x})$ are nonlinear scalar constraint functions, which can be written in a vector form as $\boldsymbol{c}(\boldsymbol{x}) = [c_1(\boldsymbol{x}), \ldots, c_m(\boldsymbol{x})]^T$. $c_i(\boldsymbol{x})$, $i = 1, \ldots, m_e$ are referred to as equality constraints, and $c_i(\boldsymbol{x})$, $i = m_e+1, \ldots, m$ are referred to as inequality constraints [14, 15].

The optimal solution for the problem defined in Equation (1) must satisfy a set of equations, known as the Kuhn-Tucker equations [16]. The Kuhn-Tucker equations thus form a necessary condition for the optimality of a solution. Furthermore, when the optimization problem is convex, so that both the objective function f and the constraints c_i shown in Equation (1) are convex, the Kuhn-Tucker equations are also necessary to achieve sufficient conditions for the global minimum point. The Kuhn-Tucker equations are written below in terms of the Lagrangian function:

$$\nabla L(x^*,\ \lambda^*) = 0 \quad (2)$$
$$c_i(\mathbf{x}^*) = 0,\ i = 1, \ldots, m_e \quad (3)$$
$$c_i(\mathbf{x}^*) \leq 0,\ i = m_e+1, \ldots, m \quad (4)$$
$$\lambda_i^* c_i(x^*) = 0,\ i = 1, \ldots, m \quad (5)$$
$$\lambda_i^* \geq 0,\ i = m_e+1, \ldots, m \quad (6)$$

Where $\nabla \boldsymbol{L}$ is the first derivative of the Lagrangian function, and $\boldsymbol{L}(\boldsymbol{x}, \boldsymbol{\lambda})$ is the Lagrangian function which can be defined as $\boldsymbol{L}(\boldsymbol{x}, \boldsymbol{\lambda}) = f(\boldsymbol{x}) + \lambda^T \boldsymbol{c}(\boldsymbol{x})$, where $\lambda=[\lambda_1, \ldots, \lambda_n]$. The condition for a minimum point becomes $\nabla \boldsymbol{L}(x^*, \lambda^*) = 0$, where λ^* are the Lagrange multipliers associated with x^*. x and λ at the solution point are denoted by x^* and λ^* respectively. These conditions do not hold if some regulatory assumptions (also called constraints qualifications) are not met [17], although this happens only in extreme cases. Equations (3) and (4) are simply re-statements of the constraints equations.

Equation (5) is related to the fact that inactive constraints at the solution point have corresponding Lagrange multipliers of zero, which means that they do not affect the solution. Indeed, inactive constraints have no effect on the solution point if they are removed. Equation (6) states that all the Lagrange multipliers of the inequality constraints are non-negative, i.e. they are zero for the inactive inequality constraints and positive for the active inequality constraints. A more detailed description of the Kuhn-Tucker conditions can be found in previous studies [16]. In this work the Sequential Quadratic Programming (SQP) method is used to solve the optimization problem. The nonlinear programming problem defined in Equation (1) can be solved iteratively by calculating the solution to a quadratic sub-problem at each iteration. The solution to the Quadratic Programming (QP) sub-problem gives the search direction for the next iteration. First, the formulation of the quadratic sub-problem will be described, and then the complete Sequential Quadratic Programming algorithm will be given. According to the Lagrangian function and the Kuhn-Tucker condition, as in Equation (2), the solution point is a stationary point of the Lagrangian function. This condition is written in a matrix form as follows:

$$\underline{\nabla} L(x^*,\ \lambda^*)=0 \qquad (7)$$

where the operator $\underline{\nabla}$ is denote to be gradient with respect to both $\boldsymbol{x}$ and $\boldsymbol{\lambda}$, i.e.
$\underline{\nabla}= [\nabla_x \nabla_\lambda]^T$.

Given a point ($\boldsymbol{x_k}$, $\boldsymbol{\lambda_k}$), and by approximating the Lagrangian function with a quadratic function (using truncated Taylor series), an approximation to (x^*, λ^*) can be found by minimizing the approximated quadratic function. A truncated Taylor series expansion is used to approximate Equation (8), for the point ($\boldsymbol{x_k}+\boldsymbol{\delta_x}$, $\boldsymbol{\lambda_k}+\boldsymbol{\delta_\lambda}$) around the point ($\boldsymbol{x_k}$, $\boldsymbol{\lambda_k}$), as in the following equation:

$$\underline{\nabla} L(x_k+\delta_x, \lambda_k+\delta_\lambda) \approx \underline{\nabla}\, L(x_k, \lambda_k) + \underline{\nabla}^2\, L(x_k, \lambda_k)[\delta_x \delta_\lambda]^T \quad (8)$$

where $\underline{\nabla}^2$ is the Hessian matrix with respect to both $\boldsymbol{x}$ and $\boldsymbol{\lambda}$. It is required that the point ($\boldsymbol{x_k}+\boldsymbol{\delta_x}$, $\boldsymbol{\lambda_k}+\boldsymbol{\delta_\lambda}$) will approximate ($\boldsymbol{x}^*$, $\boldsymbol{\lambda}^*$), and the left-hand side of Equation (8) is set to zero, which, according to the Kuhn-Tuker conditions, will occur at the solution point. Evaluating the right-hand side of Equation (8), after some manipulation [14], and setting

$$\lambda_{k+1} = \lambda_k + \delta_\lambda,\ d_k = \delta_x \quad (9)$$

yields the results in the following equation, where only gradients with respect to $\boldsymbol{x}$ are included (for notational convenience, the condition of ∇_x=∇ is required):

$$\underline{\nabla}^2\boldsymbol{L}(\boldsymbol{x_k}, \boldsymbol{\lambda_k})\boldsymbol{d_k}+\nabla\boldsymbol{c}(\boldsymbol{x_k})^T\boldsymbol{\lambda_{k+1}} +\nabla f(\boldsymbol{x_k}) = 0$$
$$\nabla\boldsymbol{c}(\boldsymbol{x_k})^T \boldsymbol{d_{k+1}} + \boldsymbol{c}(\boldsymbol{x_k}) = 0 \quad (10)$$

The quadratic function and linear constraints (i.e. a QP problem) are now defined in the following way:

$$\underset{d_k}{\boldsymbol{Minimize}}\frac{1}{2}d_k^T\nabla^2L(x_k,\lambda_k)d_k + \nabla f(x_k)^T d_k = 0$$
$$\textbf{Subject to}\nabla c_i(x_k)^T d_k + c_i(x_k) = 0(11)$$

Equation (10) corresponds to the Kuhn-Tucker condition in Equation (11), i.e. the gradient of the Lagrangian function is zero. This means that the solution to the QP problem in Equation (11), which produces d_k and the corresponding Lagrange multipliers λ_{k+1}, gives an approximation of the solution point of the original nonlinear programming problem, i.e. $x^*\approx x_k+d_k$, and $\lambda^*=\lambda_{k+1}$, where the approximation arises from the quadratic approximation of the Lagrangian function. Therefore, the quadratic sub-problem in Equation (11) can be used in an iterative procedure, where in each iteration the solution to the sub-problem gives a search direction d_k for the solution of the nonlinear problem, and an update of the Lagrange multipliers. For the following sub-problem, Equation (11) can be generalized to include inequality constraints [16], which correspond to the nonlinear optimization problem in Equation (11):

$$\underset{d_k}{\boldsymbol{Minimize}}\frac{1}{2}d_k^T\nabla^2L(x_k,\lambda_k)d_k + \nabla f(x_k)^T d_k = 0$$
$$\textbf{\textit{Subject to}}\nabla c_i(x_k)^T d_k + c_i(x_k) = 0,\ i = 1, \ldots, m_e$$
$$\nabla c_i(x_k)^T d_k + c_i(x_k) \le 0,\ i = m_e+1, \ldots, m \quad (12)$$

The algorithm which solves the nonlinear programming problem using Sequential Quadratic Programming is outlined as follows:

SQP algorithm

(1) Set initial feasible point $\boldsymbol{x_0}$ and initial Lagrange multipliers $\boldsymbol{\lambda_0}$. Set k=0.
(2) Check termination conditions for $\boldsymbol{x_k}$ or k.
(3) Update the estimate of the Hessian matrix $\underline{\nabla}^2\boldsymbol{L}(\boldsymbol{x_k}, \boldsymbol{\lambda_k})$ (the updating methods will be described later).
(4) Formulate and solve the quadratic sub-problem for iteration k, as in Equation (12). Find $\boldsymbol{\lambda_{k+1}}$ and $\boldsymbol{d_k}$.
(5) Perform a line search to find α that will produce sufficient decrease in theobjective function of the original nonlinear problem at the point $\boldsymbol{x_k}+\alpha\boldsymbol{d_k}$ for $\alpha \in [0,1]$.
(6) Update $\boldsymbol{x_{k+1}}=\boldsymbol{x_k}+\alpha\boldsymbol{d_k}$.
(7) Update k=k+1 and return to stage.

In order to complete the discussion of the SQP algorithm, the updating of the Hessian matrix and the line search methods will be described. These are necessary because the Lagragian function is not quadratic for a general nonlinear problem, implying that the Hessian matrix differs for different $\boldsymbol{x_k}$, and thus must be updated along the iterations, and the solution $\boldsymbol{x_k}+\boldsymbol{d_k}$ of the QP sub-problem might not be close to the solution of the nonlinear problem since it is generally not quadratic. Thus, $\boldsymbol{d_k}$ is used only as a direction vector for the solution, and a suitable α is found so that the original objective function is significantly reduced. The method used for updating the Hessian matrix and for performing the line search can be expressed as follows (H_k denotes the Hessian matrix at iteration k):

$$H_{k+1} = H_k + \frac{q_k q_k^T}{q_k^T s_k} - \frac{H_k^T H_k}{s_k^T H_k s}(13)$$

where $s_k = x_{k+1} - x_k$,$q_k = \nabla(x_{k+1},\lambda_k) - \nabla L(x_k,\lambda_k)$

During the updating process, measures are taken (such as the modification of $\boldsymbol{q_k}$) to keep $\boldsymbol{H_{k+1}}$ positive, which ensures that the quadratic sub-problem will have a unique minimum. The line search is conducted to find an appropriate α such that a significant decrease in a merit function, which includes both the objective function and the constraints, is obtained. The merit function is described as:

$$\psi(x) = f(x) + \sum_{i=1}^{m_e}\sigma_i c_i(x) + \sum_{i=m_e+1}^{m}\sigma_i \max\{0, c_i(x)\}\ (14)$$

where violated constraints are used to penalize the merit function, and $\sigma_i$are used as the penalty coefficients.

The SQP method is used in this work to find the optimal solution of the control problem in a finite number of iterations. Commercially available software exists to solve SQP problems, such as the MATLAB *fmincon*() function. The main objective of the optimization method proposed in this study is to modulate the original engine sound to the desired engine sound. The formulation of the optimization approach proposed in the work for modulating the engine sound can be expressed as:

Minimize$\| e \|_2^2 = \| d_d - (d_p + d_s) \|_2^2$ (15)

This d_d is the desired sound, d_p is the primary sound and d_s is the secondary sound. After d_p and d_s are superimposed, hoping to close to d_d, the expected new engine sound, it will be minimized forming an error value in Equation(15). Fig. 2 shows the block diagram of active engine sound design.Loudspeakers are placed in the vehicle cabin. The loudspeakers introduce additional sound inside the vehicle cabin. The loudspeaker's driving signal is calculated in a controller and passes through an amplifier. To obtain a realistic sound the loudspeaker driving strategies must be defined. Those driving strategies are implemented in the controller.

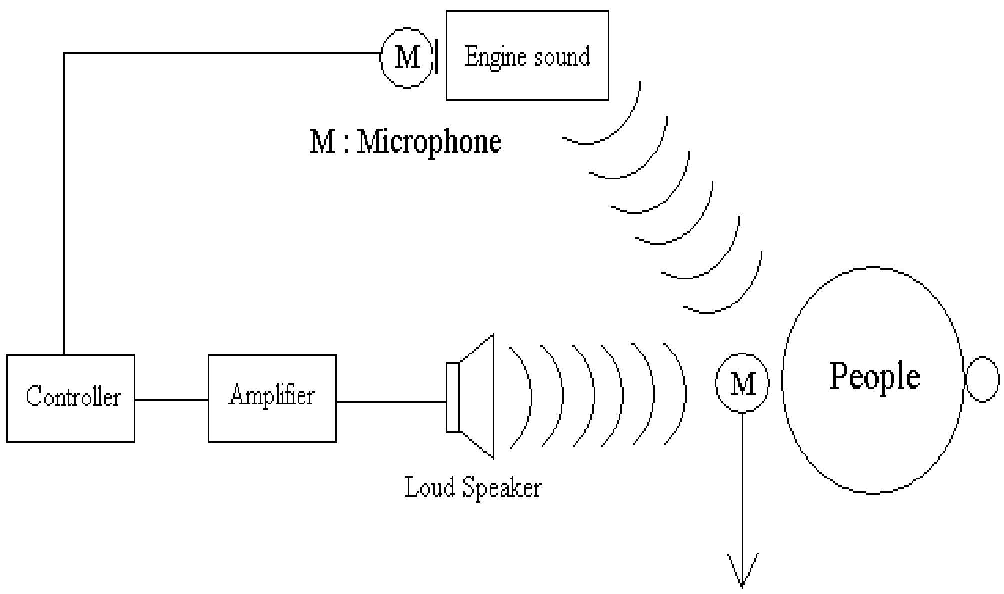

Figure 1 Active design of engine sound.

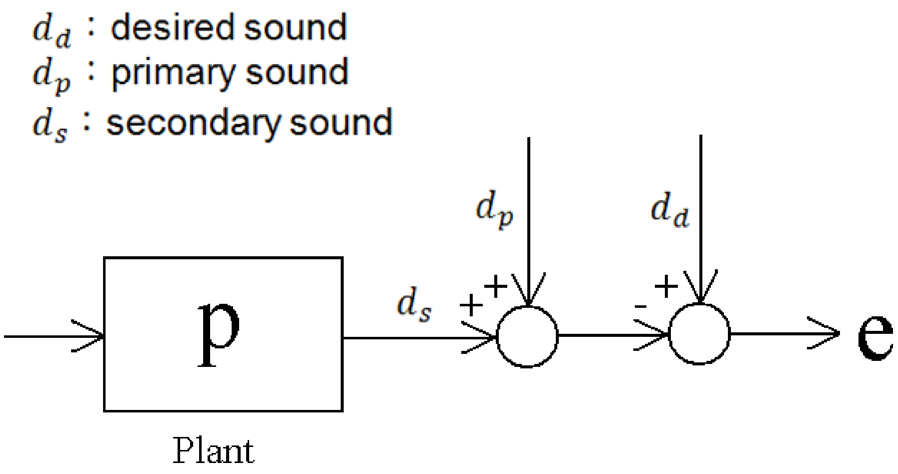

Figure 2 The block diagram of active engine sound design.

e **headings** and **subheadings**, starting with "**1. Introduction**", appear in upper and lower case letters and should be **set in bold and aligned flush left**. All headings from the Introduction to Acknowledgements are numbered sequentially using 1, 2, 3, etc. Subheadings are numbered 1.1, 1.2, etc. If a subsection must be further divided, the numbers 1.1.1, 1.1.2, etc.

The font size for **heading is 11 points bold face** and **subsections with 10 points and not bold.** Do not underline any of the headings, or add dashes, colons, etc.

III.EXPERIMENTAL RESULTS

The objective of this simulation is to transfer the corolla altis engine sound to the super sentra engine sound. The corolla altis engine sound is measured and fed into controller. The controller calculates the optimal engine sound signal and then sent to the loudspeaker creating the modulating engine sound. Fig. 3 shows the spectrum of engine sound for corolla altis at 800 rpm. Fig.4 shows the spectrum of engine sound for super sentra at 800 rpm. Fig. 5 shows the spectrum of the superposition engine sound for altis and the secondary source at 800 rpm. From the figure it can be seen that the engine sound for altis is very similar to that for sentra through modulating.Fig. 6 shows the spectrum of the engine sound difference between modulated corolla altis engine sound and super sentra engine sound at 800rpm.

Fig. 7 shows the spectrum of engine sound for corolla altis at 1000 rpm. Fig. 8 shows the spectrum of engine sound for super sentra at 1000 rpm. Figure 9 shows the spectrum of the superposition engine sound for altis and the secondary source at 1000 rpm. From the figure it can be seen that the engine sound for altis is very similar to that for sentra through modulating. Fig.10 also shows the spectrum of the engine sound difference between modulated corolla altis engine sound and super sentra engine sound at 1000rpm.

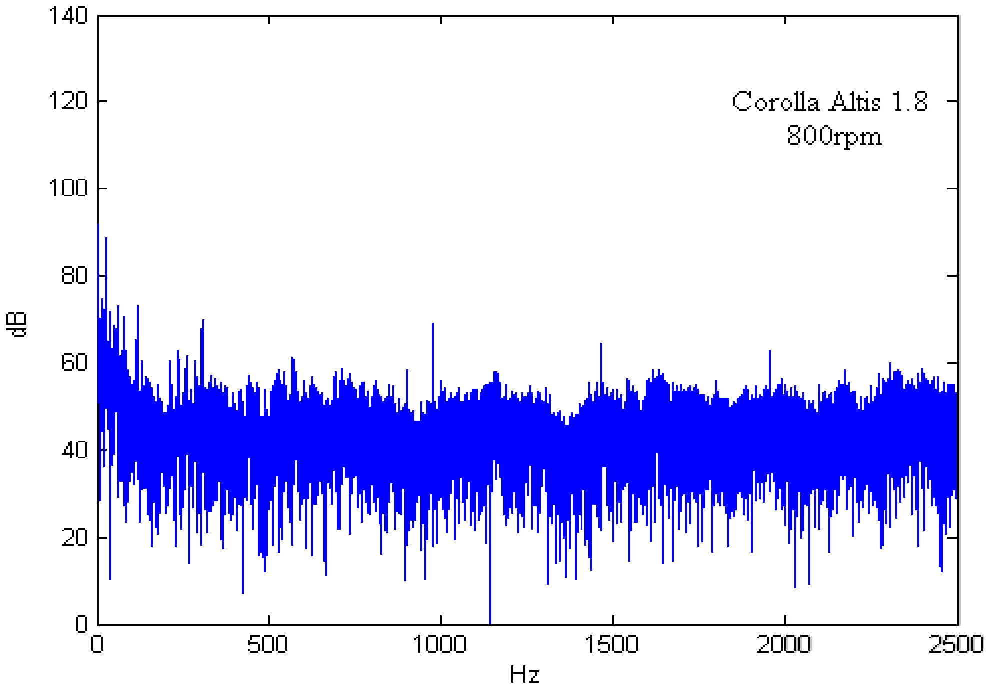

Figure 3 The spectrum of engine sound for corolla altis at 800 rpm.

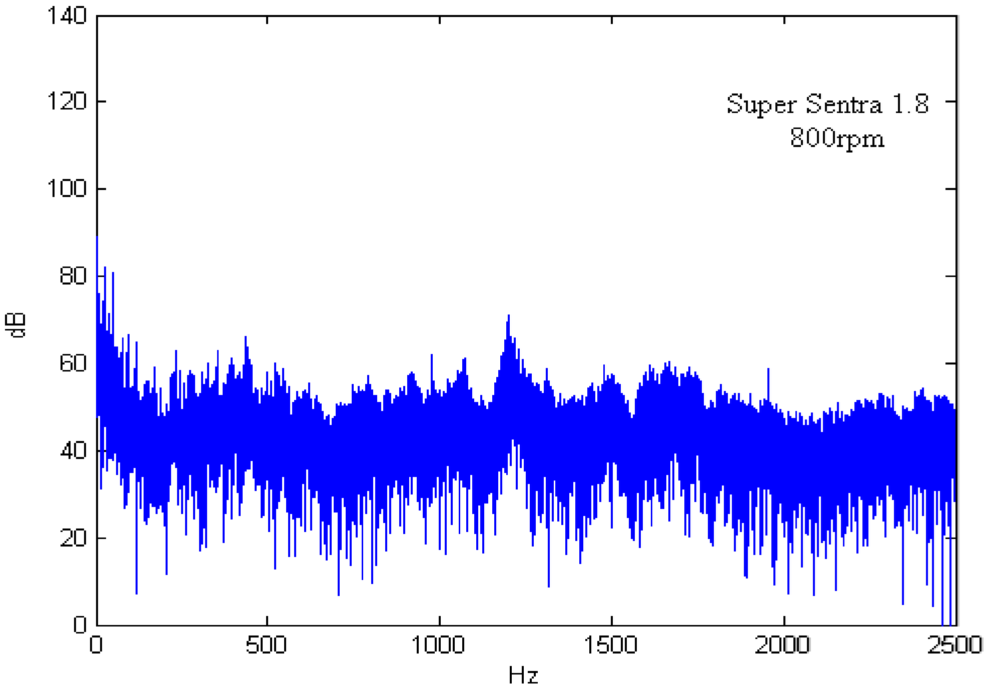

Figure 4 The spectrum of engine sound for super sentra at 800 rpm.

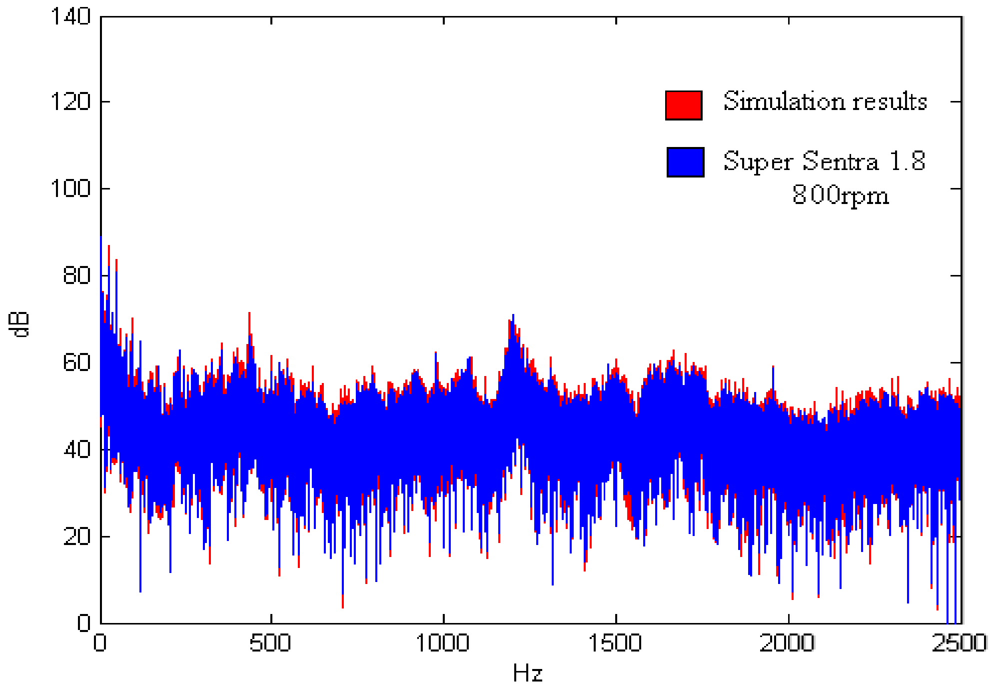

Figure 5 The spectrum of the superposition engine sound for altis and the secondary source at 800 rpm.

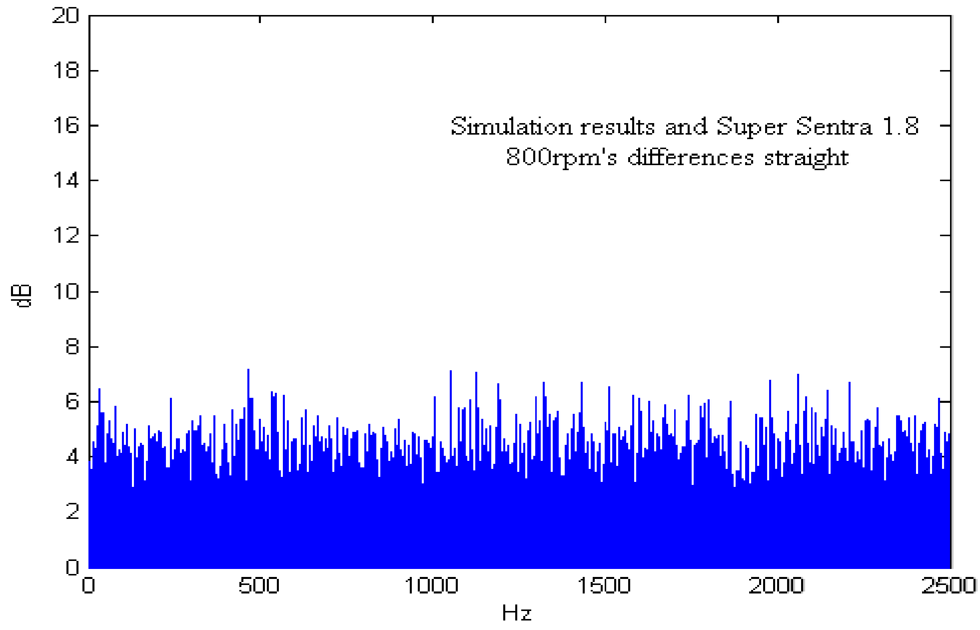

Figure 6 The spectrum of the engine sound difference between modulated corolla altis engine sound and super sentra engine sound(800rpm).

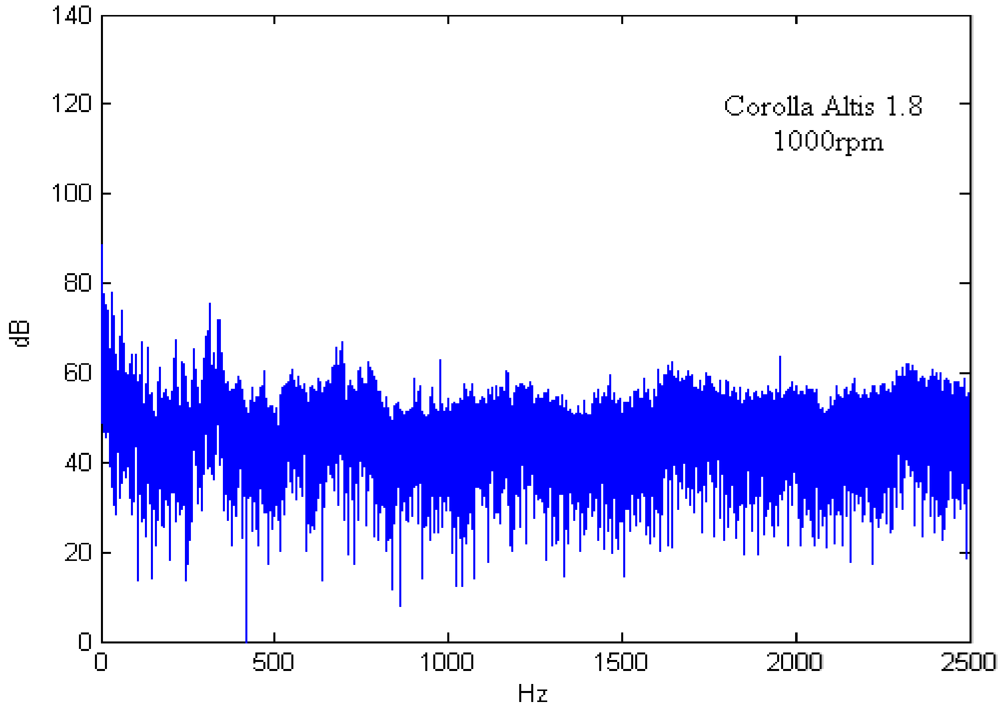

Figure 7 The spectrum of engine sound for corolla altis at 1000 rpm.

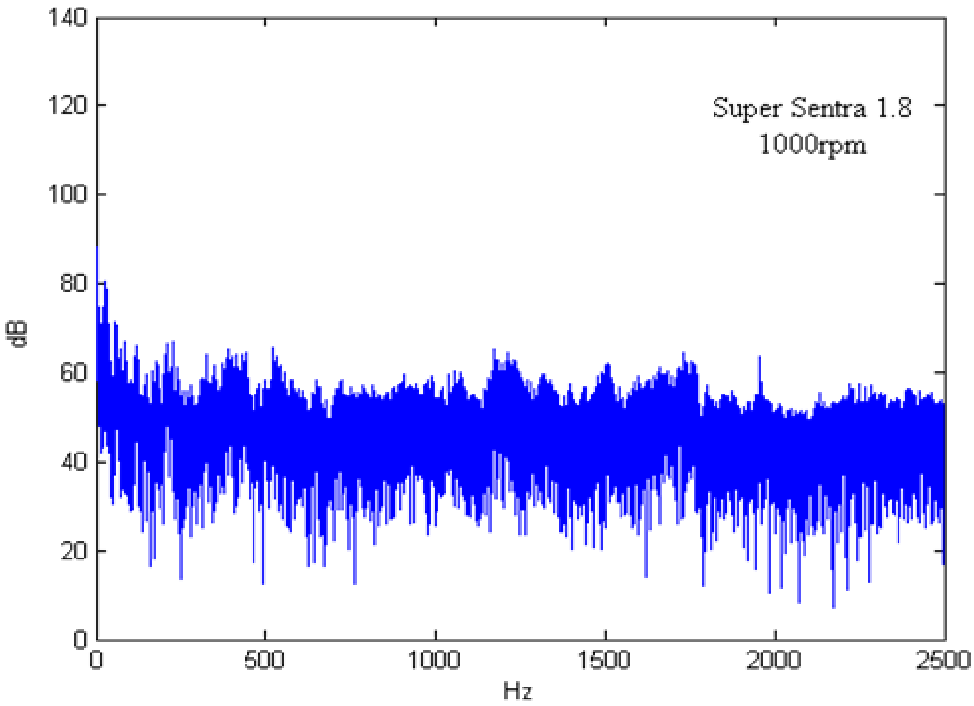

Figure 8 The spectrum of engine sound for super sentra at 1000 rpm.

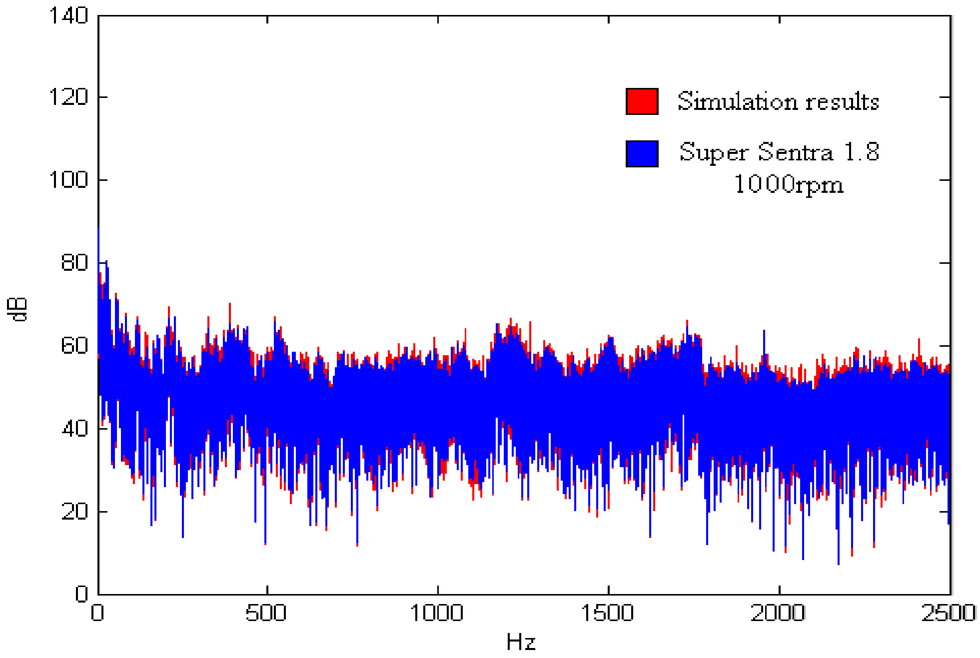

Figure 9 The spectrum of the superposition engine sound for altis and the secondary source at 1000 rpm.

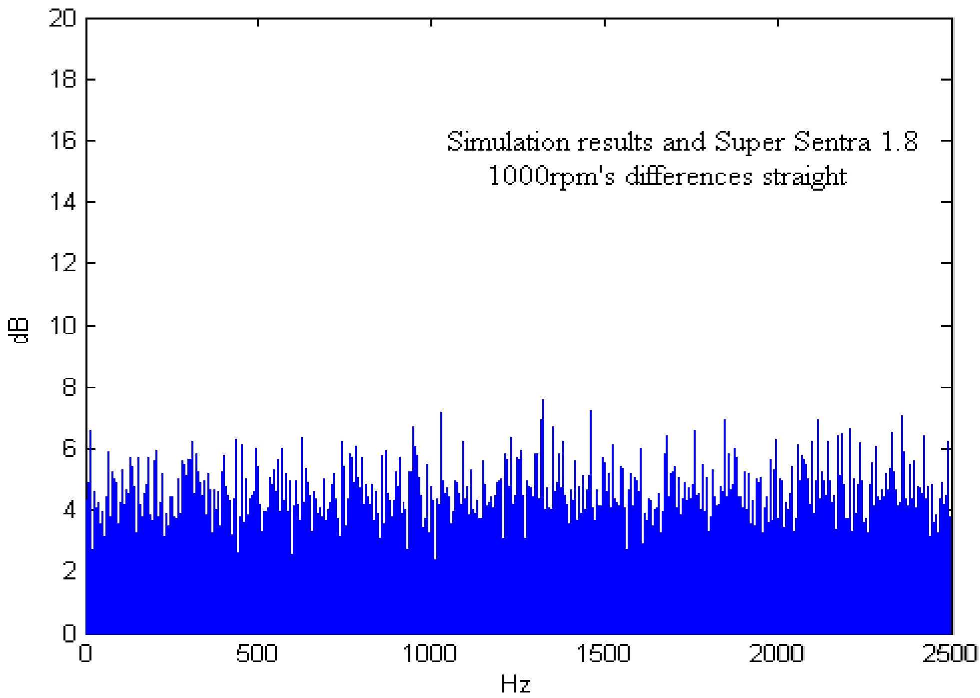

Figure 10 The spectrum of the engine sound difference between modulated corolla altis engine sound and super sentra engine sound(1000rpm).

IV.CONCLUSIONS

This study investigated performance of active engine sound design using a proposed active sound design method. An optimization method has been used to design the controller to produce desired engine sound. The desired engine sound depended on the engine speed varying from idle to 3000 rpm. The original engine sound could be modified to the desired engine sound. The results showed that the original engine sound could be modified to the desired brand engine sound. The good performance of the active engine sound design has been achieved and the spectrum difference between the original and the desired engine sound was very small. Therefore the proposed method in the study could be useful for active engine sound design. Also this active engine sound design could be applied to any vehicles.

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