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Parameter-setting-free algorithm to determine the individual sound power levels of noise sources

적응형 파라미터 알고리즘을 이용한 개별 소음원의 음향파워 예측 연구

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ABSTRACT

PURPOSES : We propose a parameter-setting-free harmony-search (PSF-HS) algorithm to determine the individual sound power levels of noise sources in the cases of industrial or road noise environment.

METHODS : In terms of using methods, we use PSF-HS algorithm because the optimization parameters cannot be fixed through finding the global minimum.

RESULTS : We found that the main advantage of the PSF-HS heuristic algorithm is its ability to find the best global solution of individual sound power levels through a nonlinear complex function, even though the parameters of the original harmony-search (HS) algorithm are not fixed. In an industrial and road environment, high noise exposure is harmful, and can cause nonauditory effects that endanger worker and passenger safety. This study proposes the PSF-HS algorithm for determining the PWL of an individual machine (or vehicle), which is a useful technique for industrial (or road) engineers to identify the dominant noise source in the workplace (or road field testing case).

CONCLUSIONS : This study focuses on providing an efficient method to determine sound power levels (PWLs) and the dominant noise source while multiple machines (or vehicles) are operating, for comparison with the results of previous research. This paper can extend the state-of-the-art in a heuristic search algorithm to determine the individual PWLs of machines as well as loud machines (or vehicles), based on the parameter-setting-free harmony-search (PSF-HS) algorithm. This algorithm can be applied into determining the dominant noise sources of several vehicles in the cases of road cross sections and congested housing complex.

Keywords
Parameter-setting-free, Harmony-search algorithm, Noise, Sound power level

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1. INTRODUCTION

This study proposes the PSF-HS algorithm for determining the PWL of an individual machine (or vehicle), which is a useful technique for industrial (or road) engineers to identify the dominant noise source in the workplace (or road field testing case). Using the novel technique, we can evaluate whether industrial workers can be exposed to a noise hazard due to the multiple noise sources. This technique can be used to find the dominant noise sources; then, the noise sources can be controlled by reducing or turning off them, in order to stop causing workers' hearing damage.

The hearing damage caused by noise is directly related to the amount of acoustical energy reaching the hearing mechanism (Vér and Beranet, 2006; Mun and Geem, 2009a). Hence, the major factors in noise-related hearing damage are the level of the noise source, the duration of the noise exposure, and the susceptibility of the human ear. For these reasons, it is important to find the individual sound power levels (PWLs) of multiple machines running in working places, as well as the dominant machines (or vehicles) producing loud noises, even when measurements of the noise sources are limited.

This paper extends the state-of-the-art in a heuristic search algorithm to determine the individual PWLs of machines as well as loud machines (or vehicles), based on the parameter-setting-free harmony-search (PSF-HS) algorithm.

The original harmony-search (HS) algorithm mimicked the behavior of musicians during improvisation to produce a better state of harmony (Geem et al., 2001; Lee et al., 2005; Mun and Geem, 2009a and 2009b; Mun and Lee, 2011; Mun and Cho, 2012; Lee and Mun, 2014). The HS algorithm mimics a behavioral phenomenon of musicians in the improvisation concert, where each musician continuously tries to experiment and improve his or her contribution in order to find a better state of harmony (Kang and Geem 2004; Lee and Geem 2004). Thus, the heuristic harmony search (HS) algorithm has been used to solve complex optimization problems that are known to be difficult for the traditional optimization techniques (Fung, et al., 2002). The HS algorithm is known as providing several benefits when compared with traditional calculus-based optimization techniques that generally require certain mathematical properties such as differentiability, continuity, and convexity.

When several constraint problems are considered using the HS algorithm, some difficulties can be encountered because the HS algorithm is blind to constraints. In such a circumstance, it is very likely that the randomly generated solution vectors can be found in infeasible region due to certain constraints. The constraint handing methods, which are commonly used, are the penalty and repair methods (Fung et al., 2002; Chootinan and Chen, 2006). In order to solve these problems, several penalty methods have been widely used by converting the constraint problems into an unconstraint ones through augmenting the constraints to the objective function as a penalty term (Chootinan and Chen, 2006).

The original harmony search consists of five steps as follows: The algorithm parameters are specified in Step 1 as follows: the harmony memory size (HMS) is the number of solution vectors in the harmony memory (HM); the harmony memory considering rate (HMCR between 0 and 1) is the rate of memory consideration, and the pitch adjusting rate (PAR between 0 and 1) is the rate of pitch adjustment. The maximum number of improvisations or stopping criterion is also defined.

In Step 2, the HM matrix is initially obtained from many randomly generated solution vectors as the HMS, as well as from the corresponding objective function value, f(X):

$$\mathrm{HM}=\left[\begin{array}{cccc|c} x_1^1 & x_2^1 & \cdots & x_N^1 & f(\mathrm{X}^1) \\ x_1^2 & x_2^2 & \cdots & x_N^2 & f(\mathrm{X}^2) \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_N^{HMS} & f(\mathrm{X}^{HMS}) \end{array}\right], \tag{1}$$

In Step 3, a new harmony vector, $\mathrm{X}'=(x_1', x_2', \cdots, x_N')$, is improvised based on the following three mechanisms: (1) random selection, (2) harmony memory consideration, and (3) pitch adjustment. The value of each decision variable obtained by the memory consideration is examined to determine whether it should be pitch-adjusted. This operation uses the PAR parameter, which ranges between 0 and 1. If the pitch adjustment decision for x_i' is made with a probability of the PAR, x_i' is replaced with $x_i' \pm rand \times bw$, where *rand* and *bw* are random numbers (e.g., values between 0 and 1) and a bandwidth between the lower and upper bounds, respectively. The value of (1 − PAR) sets the rate of performing nothing. Thus, the pitch adjustment is applied to each variable as

$$x_i' \leftarrow \begin{cases} x_i' + rand \times bw, \text{ with a probability of } \mathrm{HMCR} \times \mathrm{PAR} \times 0.5 \\ x_i' - rand \times bw, \text{ with a probability of } \mathrm{HMCR} \times \mathrm{PAR} \times 0.5. \\ x_i', \text{ with a probability of } \mathrm{HMCR} \times (1-\mathrm{PAR}) \end{cases} \tag{2}$$

In Step 4, a matrix update process occurs. For example, if the newly generated harmony vector is better than the worst harmony in the HM, based on the evaluation of an objective function value, the newly generated harmony is included in the HM and the existing worst harmony is excluded from the HM.

In Step 5, if the stopping criterion (or maximum number of improvisations) is satisfied, the computation is terminated. Otherwise, Steps 3 and 4 are repeated.

2. MATHEMATICAL MODELING of the PSF-HS ALGORITHM

As shown in the original HS algorithm, the algorithm parameters such as the HMCR and PAR are fixed as

$$\mathrm{HMCR} = R_{Memory} + R_{Pitch} \text{ and } \mathrm{PAR} = \frac{R_{Pitch}}{R_{Memory} + R_{Pitch}}, \quad \text{(3a and 3b)}$$

where R_{Memory} is the rate of harmony memory consideration only at the HM matrix and R_{Pitch} is the rate of pitch adjustment, as defined in Eq. (2). According to the PSF-HS algorithm (Geem and Sim, 2010), a three-step procedure to eliminate the parameter-setting efforts can be used. First, a random tuning procedure is performed. This step generates random vectors, as shown in Eq. (1). Second, a rehearsal step is followed to produce certain amounts of new vectors in the HM, with initial parameter values for the HMCR and PAR set to 0.25 and 0.25, respectively. In this step, an additional matrix of the rehearsal memory (RM) is saved in computer memory to trace the individual element operation of random selection, harmony memory consideration, or pitch adjustment:

$$\mathrm{RM} = \begin{bmatrix} y_1^1 = Random & y_2^1 = Random & \cdots & y_N^1 = Memory \\ y_1^2 = Pitch & y_2^2 = Memory & \ldots & y_N^2 = Pitch \\ \vdots & \vdots & \cdots & \vdots \\ y_1^{HMS} = Random & y_2^{HMS} = Pitch & \cdots & y_N^{HMS} = Random \end{bmatrix}, \quad (4)$$

where $Random$ is the random selection, $Memory$ is the harmony memory consideration at the HM matrix only, and $Pitch$ is the pitch adjustment. Third, a performance step is applied to determine the heuristically updated ratios of R_{Memory} and R_{Pitch}, based on observations of the column vector in the RM matrix. For example, the ratios of R_{Memory} and R_{Pitch} can be obtained by counting the number of $Memory$ and $Pitch$ selections, respectively:

$$\mathrm{R}_{\mathrm{Memory}\,i} = \frac{\mathrm{NMem}_i}{\mathrm{HMS}} \text{ and } \mathrm{R}_{\mathrm{Pitch}\,i} = \frac{\mathrm{NPi}_i}{\mathrm{HMS}}, \quad \text{(5a and 5b)}$$

where $\mathrm{R}_{\mathrm{Memory}\,i}$ and $\mathrm{R}_{\mathrm{Pitch}\,i}$ are the ratios of R_{Memory} and R_{Pitch} in the i^{th} column of the RM matrix, and NMem_i and NPi_i are the number of $Memory$ and $Pitch$ selections in the i^{th} column of the RM matrix. Thus, the ratios of R_{Memory} and R_{Pitch} are determined by calculating Eqs. 5a and 5b. Hence, the ratios can be used for a newly generated solution vector. If the new solution vector is better than the worst one in the HM, the worst vector is replaced by it. Finally, if the stopping criterion (or maximum number of improvisations) is satisfied, the PSF-HS algorithm ends. Otherwise, the above steps are repeated, as for the original HS algorithm.

2.1. Mathematical formulation of sound propagation

When formulating a mathematically sound propagation phenomenon, the following relationship between spherical sound radiation in a free field and a point source of the PWL is used (Rathe, 1969; Lu and Hong, 2005; Mun and Geem, 2009a):

$$\mathrm{SPL} = \mathrm{PWL} + 10\log_{10}\left(\frac{Q}{4\pi r^2}\right), \quad (6)$$

where SPL is the sound pressure level related to the spherical sound radiation, PWL is a point source, Q is the directivity factor of the source, and r is the distance from the source to the point of interest as shown in Fig. 1.

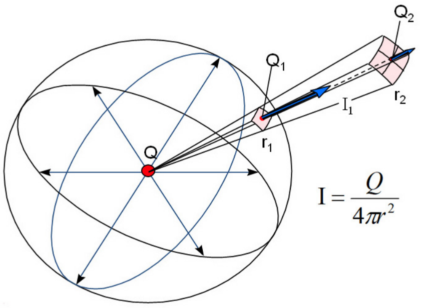

Fig. 1 Intensity used in Eq. 6 under free-field conditions

For multiple sources and measurements (Lu and Hong, 2005; Mun and Geem, 2009a), individual noise source points of the PWL and measurement points of the SPL are denoted by subscript letters, such as $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$, respectively. Therefore, multiple relationships between each PWL source and SPL measurement can be expressed by

$$\mathrm{SPL}_{ij} = \mathrm{PWL}_i + 10\log_{10}\left(\frac{Q_i}{4\pi r_{ij}^{\,2}}\right), \tag{7}$$

where SPL_{ij} is the SPL measurement at the j^{th} location, which is contributed by the PWL source at the i^{th} location; PWL_i is the PWL source at the i^{th} location; Q_i is the directivity factor of the source at the i^{th} location; and r_{ij} is the distance between the i^{th} and j^{th} locations. The multiple PWL sources influence each SPL_j at the j^{th} location. Thus, the following summation is needed to consider multiple PWL sources:

$$\mathrm{SPL}_j^{\mathrm{total}} = 10\log_{10}\left(\sum_{i=1}^{m} 10^{0.1\,\mathrm{SPL}_{ij}}\right),\ j = 1, 2, \ldots, n, \tag{8}$$

where $\mathrm{SPL}_j^{\mathrm{total}}$ is the total SPL at j^{th} location, which considers all PWL sources. Equation (8) is based on a log summation (Vér and Beranet, 2006).

2.2. Objective function

For the error objective function to be minimized through the PSF-HS algorithm, mathematical substitution of Eq. (7) into Eq. (8) is performed, yielding

$$Error = \left| \mathrm{SPL}_j^{\mathrm{total}} - 10\log_{10}\left(\sum_{i=1}^{m} \frac{Q_i}{4\pi r_{ij}^2} \times 10^{0.1\,\mathrm{PWL}_i}\right) \right|,\ j = 1, 2, \ldots, n, \tag{9}$$

where $|\bullet|$ denotes the absolute value. For simplicity when calculating total errors, the following root mean square error (RMSE) can be assigned:

$$RMSE(\vec{x}) = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left[\mathrm{SPL}_j^{\mathrm{total}} - 10\log_{10}\left(\sum_{i=1}^{m} \frac{Q_i}{4\pi r_{ij}^2} \times 10^{0.1\,\mathrm{PWL}_i}\right)\right]^2}\ , \tag{10}$$

where $\vec{x}$ is the solution column vector, i.e., $(\mathrm{PWL}_1, \mathrm{PWL}_2, \ldots, \mathrm{PWL}_m)^{\mathrm{T}}$ and $(\bullet)^{\mathrm{T}}$ denotes the transpose. Thus, the column vector $\vec{x}$ is used for the HM matrix in Eq. (1). The optimization problem can be also specified as:

$$\text{Minimize } RMSE(\vec{x}) \text{ subject to } \vec{x} \in \vec{X}, \tag{11}$$

where $\vec{X} = (X_1, X_2, \ldots, X_m)^{\mathrm{T}}$ is the possible range vector for each decision variable, i.e., $Lx_i \le X_i \le Ux_i$; and Lx_i and Ux_i denote the lower and upper bounds for each decision variable, respectively.

3. COMPARISONS and CONCLUDING REMARKS

Following a previous paper (Mun and Geem, 2009a), four cases are used in this comparison study. A manufacturing facility has two, three, four, or five machines on its factory floor, and the SPLs are measured at four locations, as shown in Table 1. To determine the governing noise contribution and individual PWLs of the machines, the same procedure can be used as in the previous paper (Mun and Geem, 2009a), based on five steps: 1) determine the locations of the existing machines; 2) choose the measurement locations of the SPLs without the influence of obstacles; 3) calculate the distance between the noise sources of the machines and the measurement locations of the SPLs; 4) choose the directivity of the noise sources, depending on a non-directional source

Table 1. Two-dimensional Coordinates of the Machine and Measurement Locations (Mun and Geem, 2009a)

Machine no.	Two machines (Case 1)		
	x-coordinate (m)	y-coordinate (m)	
1	0	0	
2	2	1	
Machine no.	Three machines (Case 2)		
	x-coordinate (m)	y-coordinate (m)	
1	0	0	
2	2	1	
3	2	0	
Machine no.	Four machines (Case 3)		
	x-coordinate (m)	y-coordinate (m)	
1	0	0	
2	2	1	
3	2	0	
4	1	3	
Machine no.	Five machines (Case 4)		
	x-coordinate (m)	y-coordinate (m)	
1	0	0	
2	2	1	
3	2	0	
4	1	3	
5	2	2	
Measurement no.	Measurement Locations		
	x-coordinate (m)	y-coordinate (m)	Measured SPLs (dBA)
1	1	0	93.6
2	0	2	87.9
3	2	3	85.0
4	1	1	92.1

(e.g., Q = 1) or a hard surface face (e.g., Q = 2 used for this study); 5) use the RMSE of Eq. (11), to be minimized through the PSF-HS algorithm.

Table 2 compares the results obtained using three techniques: the original harmony search (HS) algorithm, the least-squares method (LSM), and the PSF-HS algorithm. The details of the HS and LSM algorithms can be found in Mun and Geem (2009a). The PSF-HS algorithm resulted in similar or best optimized solutions in terms of the RMSEs.

Table 2. PWLs of Noise Soureces and RMSEs Obtained Using HS*, LSM*, and PSF-HS

Machine no.	Two machines' PWLs (dBA)		
	Harmony search	Least-squares method	PSF-HS
1	100.881	100.929	100.881
2	96.166	96.026	96.166
RMSE	0.0239	0.0386	0.0239
Machine no.	Three machines' PWLs (dBA)		
	Harmony search	Least-squares method	PSF-HS
1	100.812	100.844	100.8
2	96.103	96.022	96.192
3	84.711	83.961	84.632
RMSE	0.0162	0.0275	0.0001
Machine no.	Four machines' PWLs (dBA)		
	Harmony search	Least-squares method	PSF-HS
1	100.832	100.832	100.833
2	96.003	96.003	96.003
3	84.595	84.595	84.524
4	74.374	74.370	74.377
RMSE	0.0002	0.0002	0.0002
Machine no.	Five machines' PWLs (dBA)		
	Harmony search	Least-squares method	PSF-HS
1	100. 832	99.795	100.832
2	96.003	96.516	96.004
3	84.593	101.054	84.583
4	74.368	95.638	74.342
5	31.414	94.964+13.644*i* (complex number)	46.546
RMSE	0.0001	Not available	0.0001

* HS and LSM results obtained from Mun and Geem(2009a)

The RMSE values of Eq. (10) in all cases converged into the minimum points, as shown in Fig. 2. The parameters of R_{Memory} and R_{Pitch} could be heuristically chosen through the PSF-HS algorithm, as shown in Figs. 3 to 6. For example, the parameters related to the two PWLs in Case 1 were chosen through evolution, as shown in Figs. 3 and 4. The parameters

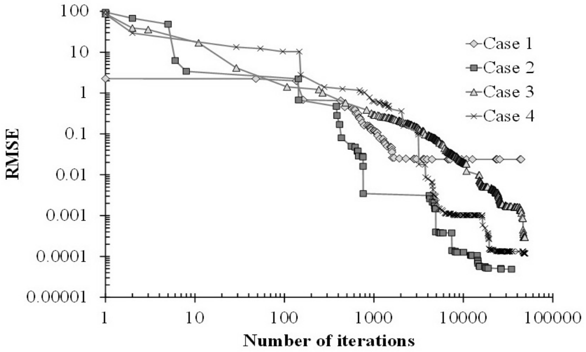

Fig. 2 RMSE Minimization Through the Number of Iterations

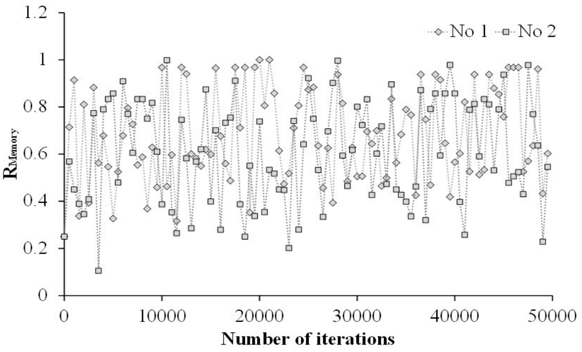

Fig. 3 Ratio of Harmony Memory Consideration vs. Number of Iterations for Case 1

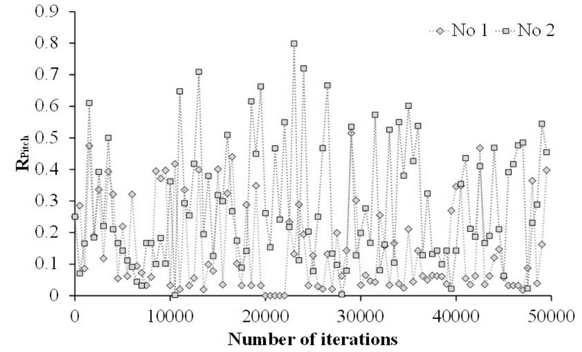

Fig. 4 Ratio of Pitch Adjustment vs. the Number of Iterations for Case 1

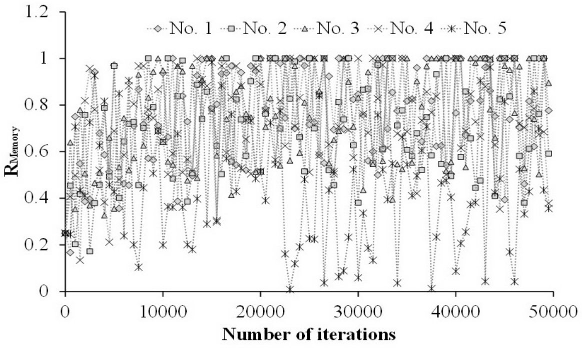

Fig. 5 Ratio of Harmony Memory Consideration vs. the Number of Iterations for Case 4

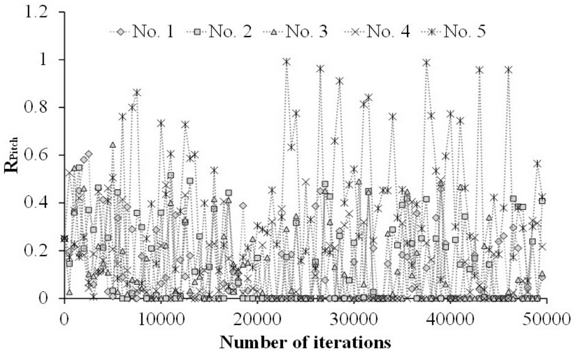

Fig. 6 Ratio of Pitch Adjustment vs. the Number of Iterations for Case 4

related to the four PWLs in Case 4 were similarly chosen, as shown in Figs. 5 and 6, without fixing the HMCR and PAR values in the original HS algorithm.

In addition, the PSF-HS algorithm can be used to determine the dominant noise source when the number of machines is less than or equal to the number of measurement points, similar to the original HS algorithm. Based on this observation, the PSF-HS algorithm can be used as an optimization engine to accurately determine the influencing noise levels of machines by measuring a few points for multiple noise sources, without setting the parameters of the original HS algorithm. Furthermore, this algorithm can be applied into determining the dominant noise sources of several vehicles in the cases of road cross sections and congested housing complex.

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