Fatigue life evaluation of construction equipment attachment structure through functional data analysis

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1. Introduction

Attachments for construction machinery generally refer to modules such as buckets, breakers, drills and grabs mounted on equipment of construction machines. According to ISO 6746-2, attachments can be mounted on equipment for special use and can be selectively assembled Called parts.

The attachment is used by converting the fluid energy from the construction machine into the impact energy, vibration energy, etc. according to the purpose of use. At this time, repetitive stress or excessive stress is generated in the high-strength steel structure used in the attachment of the construction machine. In order to secure the required reliability of the attachment, fatigue life evaluation of the strength and rigidity of the structure is necessary.

When an excessive or repetitive load is applied to the structure of the attachment, the material undergoes plastic deformation over the elastic deformation section and eventually breaks. In the elastic deformation section, when the load is removed, it is restored to its original shape. However, if the load is repeatedly applied even in the elastic deformation section, the material is destroyed. Such a fracture is called fatigue failure, and the load at that time is referred to as low load. Generally, fatigue strength against fatigue load is very important as well as strength against static load in design of machine or structure.

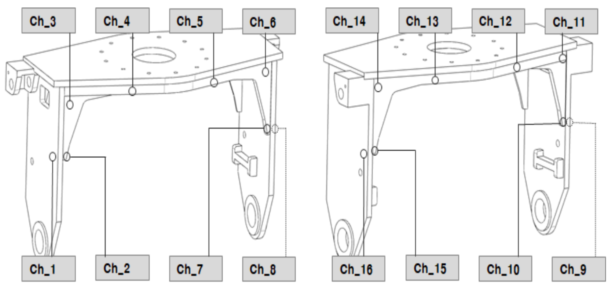
Fatigue failure can be classified into low-cycle fatigue and high-cycle fatigue depending on the type of load applied and the lifetime of the load. In the case of a relatively short life span of about 10^4 to 10^5 cycles with a load large enough to cause plastic deformation And high cyclic fatigue refers to when the load is low within the elastic range and the load is relatively long over 10^5 cycles. Three main methods for fatigue analysis are the stress-life approach, the strain-life approach, and the fracture mechanics approach

In this study, the characteristics of the field data of construction machine attachment type vibration hammer were analyzed by functional analysis, and the fatigue life of the bracket was evaluated from the analysis results and the life of the bracket was evaluated.

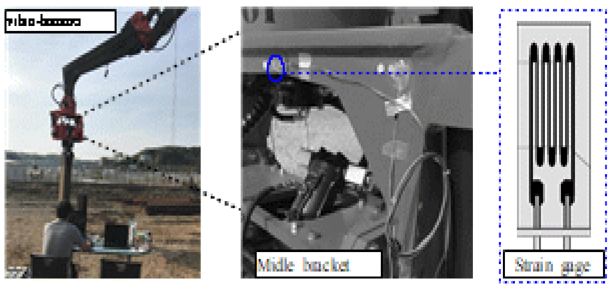
2. Securing field test data

In the middle bracket of the vibrating hammer swing module Fig. 16 strain gauges were attached as shown in Fig. 5 (a) and (b). The strain gauge used was HBM Liner SG LY41-3 / 350 model with 350 Ω nominal resistance, 2.01 gauge factor of strain gauge sensitivity and 3 mm active measuring grid length. The DAQ uses the Quantum X MX6115 model to set the data sampling to 2500 Hz. This is set considering that the operating frequency of the vibration hammer is 47 to 50 Hz.

The field test was carried out at a temperature of 13.4 ℃, a humidity of 94% and a wind speed of 2.8 m / s. As shown in Fig. 1 (c), the results of the test for measuring the strain at the beginning and at the stop of no-load operation by mounting on an excavator (Volvo EC380E) are shown in Fig. 2.

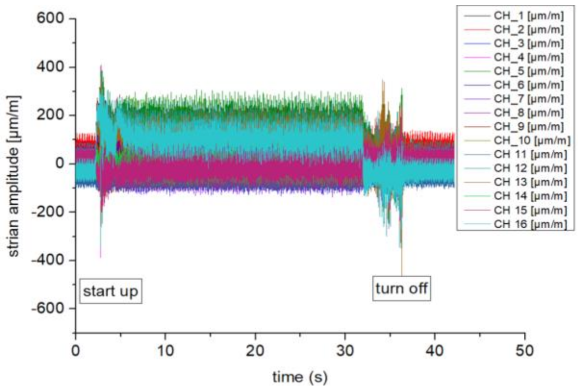


(a) Strain gage front installation (b) Strain gage rear installation

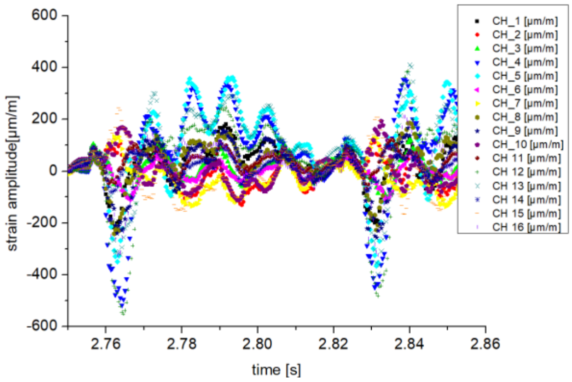


(c) Field test by operation mode

Fig. 1 Field test by operation mode and position of strain gauge



(a) Strain measurements of no-load operating



(b) Strain measurements of start-up operating

Fig. 2 Strain measurements by operating mode of no-load operating

3. Functional data analysis

Correlation analysis is a method of analyzing the linear relationship between two variables in probability theory and statistics. The two variables can be independent or correlated, and the strength of the relationship between the two variables is called a correlation. In the correlation analysis, the number of parental relations ρ is used as a unit for expressing the degree of correlation.

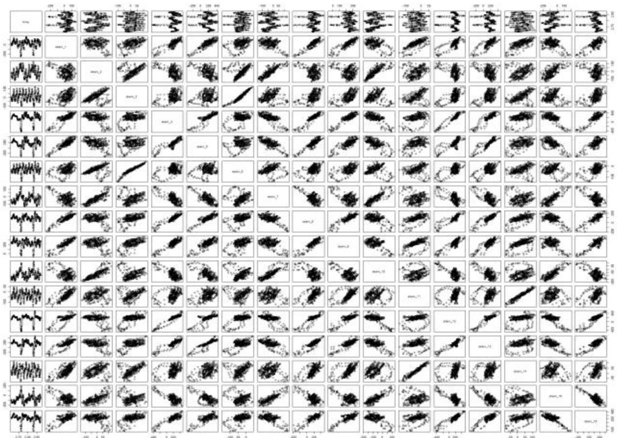


Fig. 3 Strain Data Correlation Analysis for the Operation of Vibro-Hammer Structures.

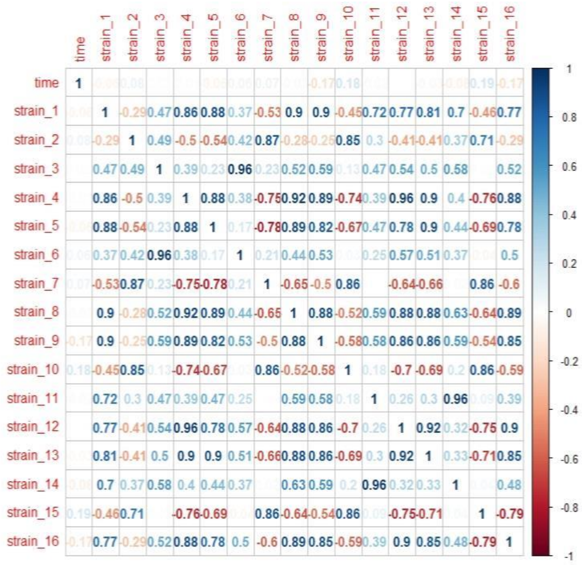


Fig. 4 Derive correlation coefficient through correlation analysis

The Pearson's correlation coefficient (Pearson's r) is commonly used to determine the relationship between two variables. The product moment correlation coefficient r is calculated as shown in Equation (1).

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}} \quad (1)$$

Where x and y are the sample mean AVERAGE (array1) and AVERAGE (array2).

The Pearson correlation coefficient was found to be the highest among strains ch00 ~ 00.

In the FDA, smoothness performs smoothness to remove minor variations present in the data.

If the least squares method obtains the following observations for a single curve, the smoothing function x can be estimated using the base expansion as follows shown in Equation (2).

$$y_j = x(t_j) + \epsilon, \quad x(t) \approx \sum_{k=1}^{K} C_k \Phi_k(t) \quad (2)$$

We can estimate c that minimizes the sum of squares error (SSE) of the next squared error.

$$SSE(c) = \sum_{j=1}^{n}(y_j - x(t_j))^2 = \sum_{j=1}^{n}(y_j - c^T\Phi(t_j))^2 \quad (3)$$

The linear regression in the basal function can be expressed as follows: SSE(Sum of Squares error) can be expressed by using the matrix when the n × K matrix is the element E and y is the vector.

$$SSE(c) = (y - \Phi_c)^T (y - \Phi_c) \quad (4)$$

C, which minimizes the SSE, is estimated by OLS (Ordinary Least Square) as follows:

$$\hat{c} = (\Phi^T \Phi)^{-1} \Phi^T y \quad (5)$$

Therefore, the smoothing function x can be estimated as follows.

$$\hat{x}(t) = \Phi(t)\hat{c} = \Phi(t)\,(\Phi^T \Phi)^{-1} \Phi^T y \quad (6)$$

The basic distribution of the residuals is the following when the least squares residual is zero and the variance is normal.

$$E(y) = \Phi c \ \text{ and } \ Var(y) = \sigma^2 I \quad (7)$$

If the standard model of the distribution of residuals is taken as the standard model, the weighted least squares method is sometimes simple and has the following characteristics.
1. y may vary depending on the time of observation
2. The residuals may be related to each other.
The first problem can be solved as follows

$$WMSE[x] = \sum w_i (y_i - x(t_i))^2 \quad (8)$$

Assuming that the matrix W is a diagonal matrix with Wi as a diagonal element, the fitted y is given by

$$\hat{x}(t) = \Phi(t)\hat{c} = \Phi(t)\,(\Phi^T W \Phi)^{-1} \Phi^T W y \quad (9)$$

$$\hat{y} = \Phi(\Phi^T W \Phi)^{-1} \Phi^T W_y = H_y \quad (10)$$

Where, H is called the smoothing matrix or the Hat matrix
As shown in Fig. 5 and 6 for ch_4 in the field strain data is represented by smoothing and 2-way function.
Where, the number of basis functions leads to less flexible modeling of a fourier basis functions and a large number of basis functions increase the flexibility of the model, but there is a question of overfitting. In the case of unary base or Fourier basis, the number of functions is increased by adding more functions.
The spline basis increases the number of knots or increases the order, which changes the base system itself and makes it more flexible.
For the second derivative function x(t), the operator D is shown in Equation (11).

$$D_x(t) = \frac{d}{dt} x(t) \quad (11)$$

The second derivative function can be expressed using the square of D.

$$D^2 x(t) = \frac{d^2}{dt^2} x(t), \ldots, D^k x(t) = \frac{d^k}{dt^k} x(t), \ldots \quad (12)$$

Where, Dx (t) is the instantaneous slope of x(t) and D2x (t) is the curvature of the function.
The magnitude of the curvature for function f is

$$PEN_2(x) = \int [D^2 x(t)]^2 dt. \quad (13)$$

In order to identify the smoothing feature, the smoothing and the second-order function are shown by applying the Fourier basis 3, 15 to distinguish start-up and turn off from the field strain data.

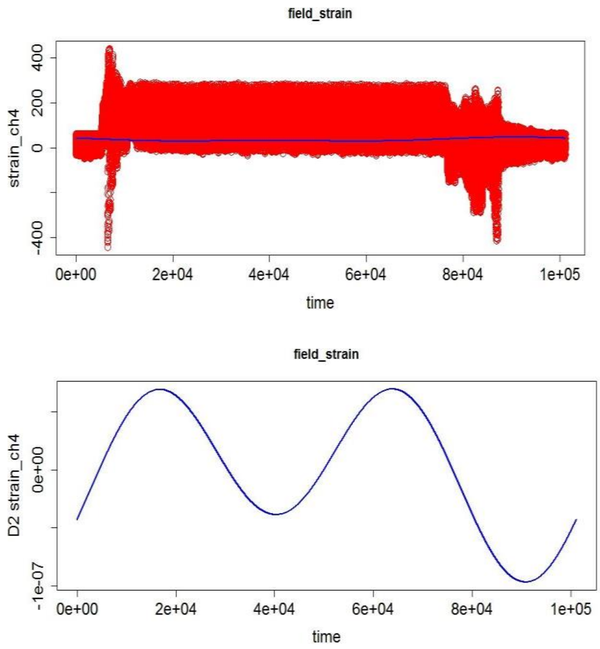
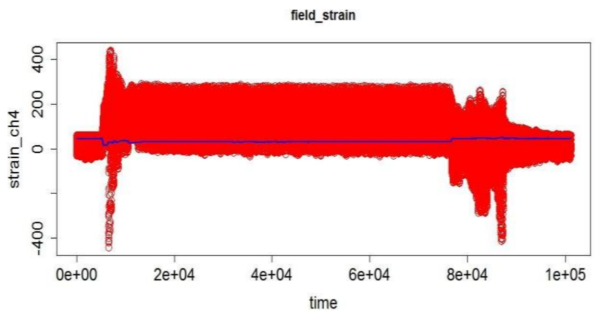


Fig 5. 3 Fourier Basis of field_strain ch4



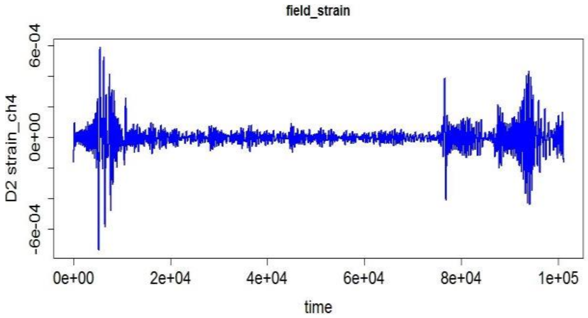


Fig 6. 503 Fourier Basis of field_strain ch4

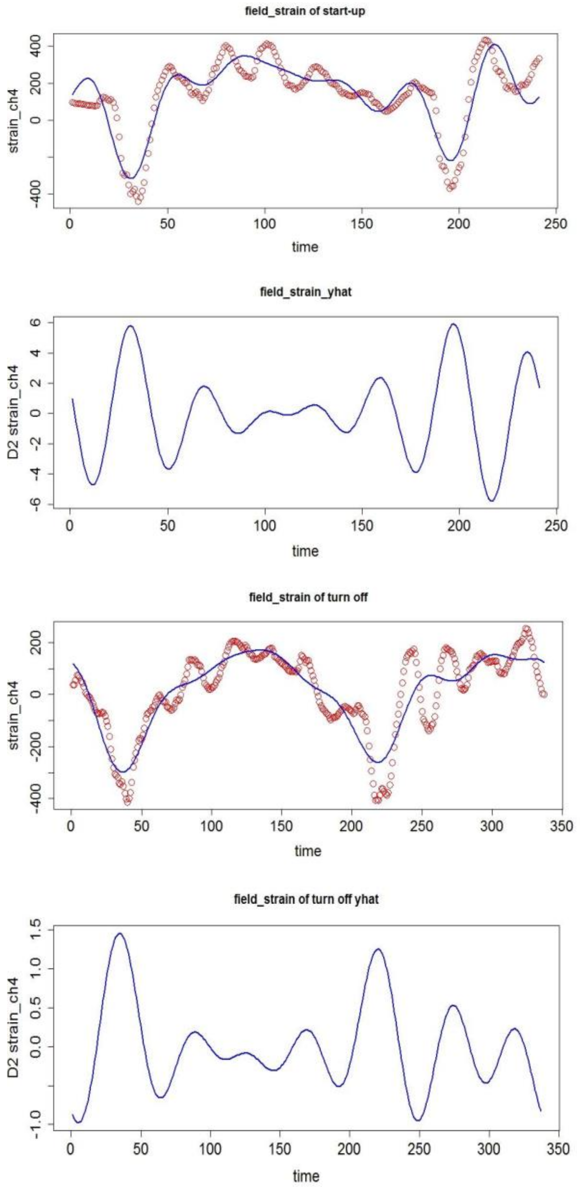


Fig 7. Fourier Bases of field_strain amplified ch4 at turn off

FPCA(Functional Principal Component Analysis) for display the corresponding eigenvalues.
Effect of relational importantness is eigenvalues.
The larger the Functional Principal Component Analysis of 241 Fourier bases, the larger the amount of variance that the entire data has.

The first and second principal component scores for each entity can be plotted.
In Fig. 9 for PC1 - represents the strain variability of the entire cycle, and there is not much difference in stopping the strain and operation of the bracket when operating the vibration hammer.
PC2- There is a large fluctuation in the start of operation and a half in stopping operation.

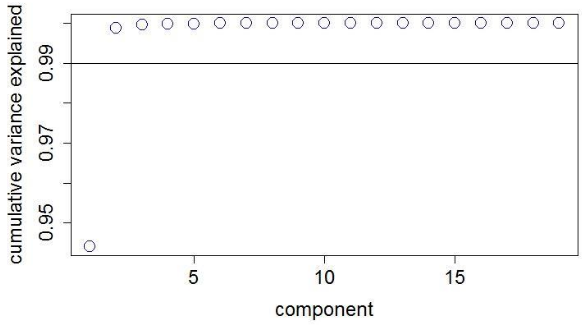


Fig 8. Cumulative variance explained Scree plot

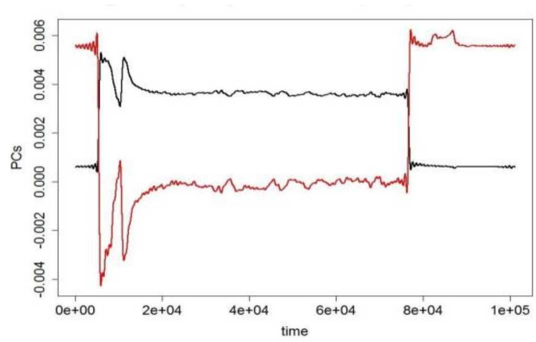


Fig 9. Principle Component Functions of field_strain

In this subspace, we try to find a base that is easier to interpret than the existing main component.
Varimax Rotation defines the subspace of a set of principal components.
This can find a coordinate system that makes the PC(principal component) loading very large or very small shown in Equation (14).

$$\text{maximize} \sum_{Var} (u_i^2) \tag{14}$$

In FDA, Varimax rotation tends to be emphasized at certain intervals.
In the graphs with argvals (argument) and armonic (harmonics), +, - sign is the result function graph by the following expression, and the solid line is the mean function.

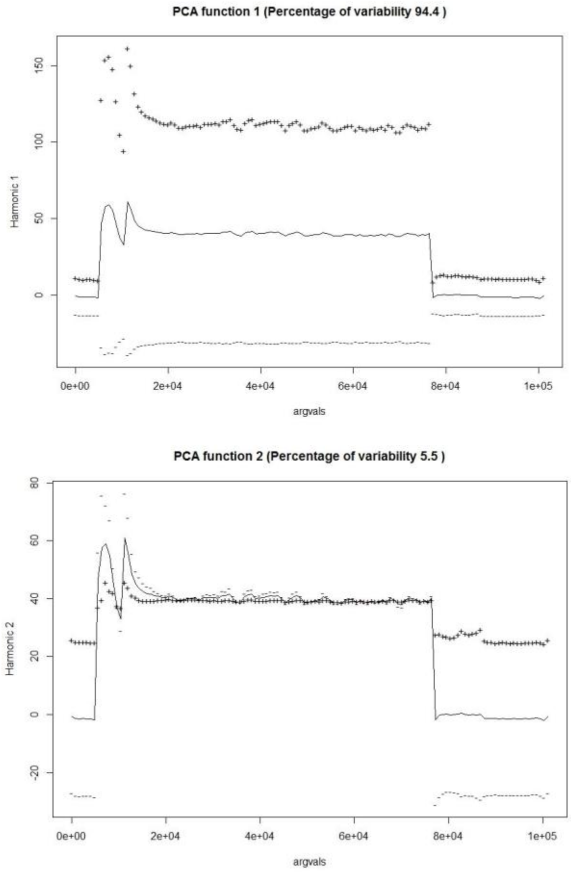


Fig 10. Principle Component Functions of field_strain

The most effective way to express the pattern of variability for each component is to add and subtract several times the principal component from the mean function shown in Equation (15).

$$\overrightarrow{x}(t) \pm \sqrt{d_i}\,\xi_i(t) \qquad (15)$$

The percentage of variability was 94.4% for the first component and 5.5% for the second component.

Therefore, it is judged that the influence of the operation when the attachment is operated and the effect when the attachment is stopped by the FDA method using the field data at the acceleration test is performed considering the strain at the start.

4. Acceleration test condition and result

Accelerated stress levels in the accelerated life test should be selected within the range that can cause the failure to be observed under the conditions of use, and the acceleration stress levels that cause failure modes that do not occur under the conditions of use should be excluded.

Therefore, selection of appropriate acceleration stress and selection of stress level are important factors in the design of accelerated life test.

The stress level for the accelerated life test shall be exceeded beyond the Specification limit, but not exceeding the Design limit of the product. In addition, the higher the level of stress, the shorter the test time, but also the uncertainty of estimation increases. Fig.11 sets the stress level, which indicates the range required for test-to-product testing to make it easier to understand.

The inverse power law model is based on torque, pressure, It is used when a non-thermal acceleration factor such as a voltage is applied. Also, the acceleration model widely used to model the product life-time as the accelerated stress function is shown in Equation (16).

$$L(T) = {}^{-}KT \qquad (16)$$

Where T: stress level
K, λ: characteristic value (constant)
Where T is the stress level, K and lambda are constants determined by the test condition characteristics of the item, i.e. the structure and experiment of the test object

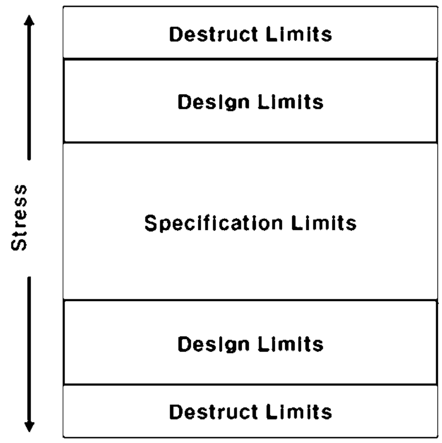


Fig. 11 Setting limit of stress level

Table 1 Accelerated life test result

max	min	strain CH.	Cycle	Time (sec)	Failure(F) Censored(C)
387.13	75.59	1	98,000	19,600	F
…	…	…	…	…	…
143.61	-45.69	4	48,000	9,600	F
232.73	3.165	5	51,000	10,200	F
…	…	…	…	…	…
277.36	-17.01	8	98,000	19,600	F
…	…	…	…	…	…
5.737	-97.37	15	117,739	23,548	C
312.83	-19.85	16	98,000	19,600	F

The vibration hammer bracket was subjected to axial load test and the fracture occurred at 48,000 cycles

Table 1 shows the results of failure by bracket position

5. Conclusion

The vibration hammer bracket was subjected to axial load test and the fracture occurred at 48,000 cycles

- The larger the variance (241 Fourier basis) of each principal component, the greater the amount of explanatory variance of the total data.
- As a result of the principal component analysis, the start-up time fluctuated greatly, and at the end, it was 1/2 level, and the first component was 94.4% and the second component was 5.5%

Acknowledgment

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References

[1] D. Y. Shin, S. Lee, U. K. Hwang, and K.W. Lee, "Technological Review of Attachments for Construction Equipment," Journal of Drive and Control , Vol. 8, No. 2, pp. 43~48

[2] G. S. Wasserman, Reliability Verification Testing and Analysis in Engineering Design, Marcel Dekker, New York, 2003.

[3] W. Nelson, "Weibull Analysis of Reliability Data with Few or No Failures," Journal of Quality Technology, Vol.17, No.3, pp.140-146, 1985.

[4] W. Nelson, Accelerated Testing; Statistical Models, Test Plans, and Data Analysis, John Wiley & Sons, Hoboken, 1990.

[5] Bannantine, J. A., Comer, J. J. and Handrock, J. L., 1997, "Fundamentals of Metal Fatigue Analysis," Prentice Hall, New Jersey, pp. 57~87

[6] Lawrence E. Kinsler., 1997, "Fundamentals of Acoustics," John Wiley & Sons Inc, pp. 15~20

[7] J. Ramsay., 2009, "Functional Data Analysis With R and MATLAB," Springer Verlag, pp. 13~40