# A Study on Emulsified Fuel Conditions and the Behavior of Diesel Engine Injection System based on Data Analysis

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# 데이터 분석 기반 유화연료 조건과 디젤엔진 분사시스템 거동에 관한 연구

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## ABSTRACT

The behavior of the injection system was determined through FFT and PSD analysis of the pressure data of the common rail, and when the diesel fuel is mixed with water, the pressure data of the common rail, depending on the water content and engine rotation speed, represent a different frequency component distribution. Recently, a theory has been suggested that mixing diesel fuel with water controls engine overheating, fuel efficiency, NOx, CO, etc., but if water content exceeds 10%, it can have a fatal adverse effect on the engine's injection system. In the future, it is necessary to promote fault diagnosis and prediction studies of diesel engines using FFT and PSD results from common rail pressure data.

Key Words : Diesel Engine(디젤엔진), Common Rail(커먼레일), Pressure Data(압력데이터), Emulsified fuel(유화연료), Injection System(분사시스템)

## 1. Introduction

Diesel engines have been widely used as power generators for ships, power plants, construction equipment, and vehicles owing to their benefits of high thermal efficiency, power, and reliability[1], but the importance of the maintenance and preservation of diesel engines has also been emphasized by problems such as air pollution caused by emissions [2].

An injection system serves as a major component in the maintenance and preservation of diesel engines, and it comprises high-pressure and low-pressure pumping systems, common rail, combustion chamber (injectors, intake/exhaust valves, pistons, and cylinders), among others. [3] As this injection system considerably affects engine performance, care should be taken to ensure regular inspections, appropriate filter and oil replacement, and fuel quality [4].

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The quality of fuel injected into an engine is a parameter that determines engine efficiency and reliability; however, it has recently been suggested that diesel fuel and water be mixed as one of the emission control methods with regard to cost-effectiveness [5]. While this method has the advantages of regulating engine overheating, fuel efficiency, NOx, CO, among others, and reducing operating costs, it is also known to adversely affect the injection system since preparing emulsified fuel at an adequate ratio is difficult, and water in the emulsified fuel causes wears, seal damages, and oxidation of the injection system [6].

Therefore, the effect of the use of emulsified fuel on the performance of a diesel engine injection system is analyzed herin by collecting the pressure data from the common rail and monitoring the behavior of the diesel engine injection system through frequency analysis to effectively understand signal characteristics and components. Quantitative criteria were also established for future studies on the failure prediction of diesel engines.

# 2. Theoretical Background

Data signals can be interpreted largely from two aspects: the amplitude of signals with time and the distribution of signals with frequency. Techniques for transforming a time domain to a frequency domain include fast Fourier Transform (FFT) and power spectral density (PSD), which decompose signals of several frequency bands into the frequency domain by decomposing and expressing arbitrary data signals with a time domain as periodic functions with various frequencies, as shown in Fig. 1 [7].

Identifying signals in the frequency domain can resolve the errors caused by noises in the time domain and provides convenience in characteristics analysis, which can be applied for preprocessing analysis and transform processing of various signals,
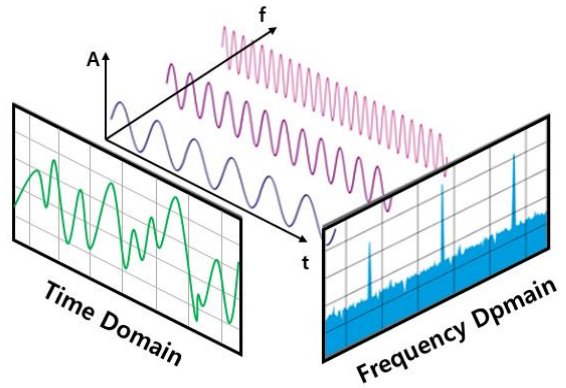


Fig. 1 A concept of fourier transform

such as images, voices, electrical signals, and biosignals [8].

## 2.1 Fast Fourier Transform(FFT)

All signals comprise complex combinations of sine and cosine functions, and analyzing these signals in a time domain can be difficult. However, Fourier Transform, shown in Eq. (1), can be used to transform a time domain into a frequency domain and analyze the frequency components and intensity that form the signals [9].

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}\,dt \qquad (1)$$

where , $X(f)$ : Frequency domain signal
$x(t)$ : Time domain signal
$f$ : Frequency

As expressed in Eq. (2), FFT compensates for the shortcoming of the Fourier Transform calculation process, which takes considerable time to complete, and it is an algorithm that processes discrete Fourier Transform at high speed [10].

$$X_k = \sum_{n=0}^{N-1} x_n e^{-j2\pi k\frac{n}{T}}, \quad K = 0, 1, ..., N-1 \qquad (2)$$

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where, $X_k$ : FFT signal

$N$ : Total number of function value

$n$ : Multiple of the basic frequency

FFT performs calculations by selecting N samples, and the larger the number of samples, the more accurate results can be obtained. Furthermore, as FFT can be easily expressed by visualizing frequency patterns as part of the signal characteristics, it is used for system defect analysis, quality control, and condition monitoring [11-12].

## 2.2 Power Spectral Density

Many waves, in reality, are "random waves" where numerous frequencies occur simultaneously. FFT is useful for wave analysis when there is a finite number of major frequency components but is limited in broadband random signal analysis. The signal also contains noises, which often makes it difficult to understand the distribution of frequency components. A methodology that overcomes this problem is PSD, wherein the FFT result is multiplied by a complex-valued component to generate a real-valued amplitude ($g^2$). This amplitude is then divided by the frequency component ($g^2/Hz$) to normalize it to the frequency bin width. Based on these characteristics, PSD is used to characterize many random signals [13].

# 3. Experimental Equipment and Method

## 3.1 Experiment Subject

A four-cylinder engine of KIA's Sorento 2004 model was used as experimental equipment to collect data. The engine specifications are listed in Table 1. As shown in Fig. 2, the diesel engine injection system comprises a high-pressure pump, common rail, injectors, ECU, and other components. The low-pressure pump of the fuel tank provides fuel to the high-pressure pump through a fuel filter, which is

then transferred from the high-pressure pump to the common rail. Some high-pressure injection systems may include a pressure regulating valve that prevents abnormal fuel flow between the outlet of the common rail and the injector accumulator chamber.

During the injection process, the fuel compressed at high pressure is directly injected into each cylinder through injectors depending on the injection timing. ECU controls the opening and closing of the injectors and supplies fuel from the high-pressure pump by sensing the pressure drop occurring in the common rail whenever fuel is injected into the cylinders.

## 3.2 Experimental Equipment

Fig. 3 shows a picture of the experimental environment, and Fig. 4 illustrates the data collection process.

**Table 1 Test engine specifications**

| Parameter | Specification |
|---|---|
| Car Model | KIA Sorento 2004 |
| Engine Type | In-line, Four(4) |
| Bore x Stroke (mm) | 91 x 96 |
| Maximum Power | 138 hp @ 3800 rpm |
| Maximum Torque (Nm/rpm) | 343 Nm @ 1900 rpm |
| Compression ratio | 17.6 |
| Fuel Injection | Common Rail |
| Aspiration | Turbocharged, intercooled |
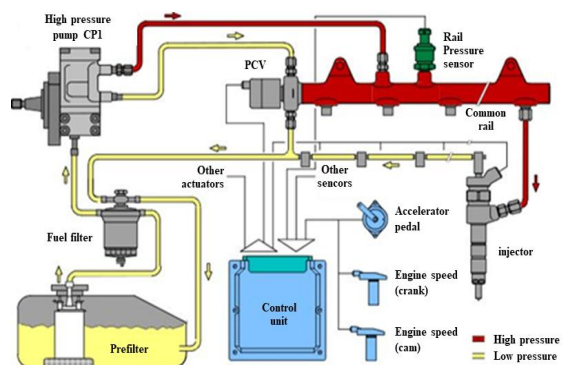


**Fig. 2 A typical common rail diesel fuel injection system**

The pressure signal was sampled from the rail pressure sensor (RPS) at 5000 Hz using NI 9228 and was stored in the.csv file format using DAQ 9178 and LabView. The pressure data of the common rail were collected under each experimental condition. All pipes connected to the fuel tank were disconnected and connected to an external fuel tank fabricated for the experiment, and a stirrer (OSA-10) was used to prepare emulsified fuel mixed with diesel fuel and water.

## 3.3 Experimental Method

As shown in Fig. 5, diesel fuel was mixed with water at water contents of 1.3%, 5%, 10%, and 20%, and the engine revolution speed was set in four stages at 900 rpm, 1,200 rpm, 1,500 rpm, and 1,700 rpm. The experiment was conducted under a total of 16 conditions, and data were collected while maintaining the engine revolution speed constant for approximately 30 min under each experimental condition. The engine was operated with pure diesel fuel for at least 1 h to flush it before collecting data under each subsequent condition.
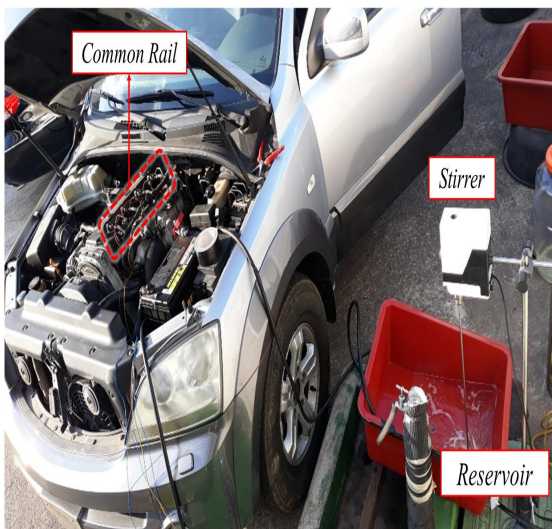


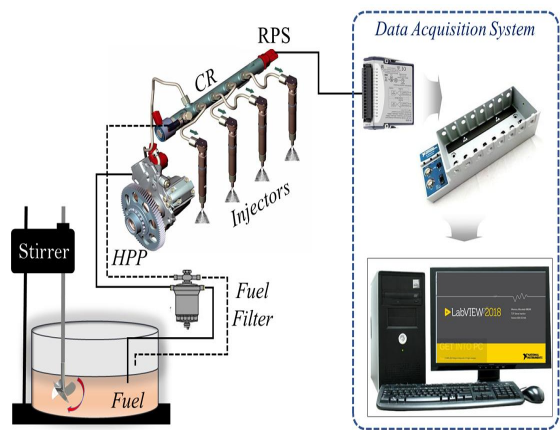Fig. 3 A picture of actual experimental setup



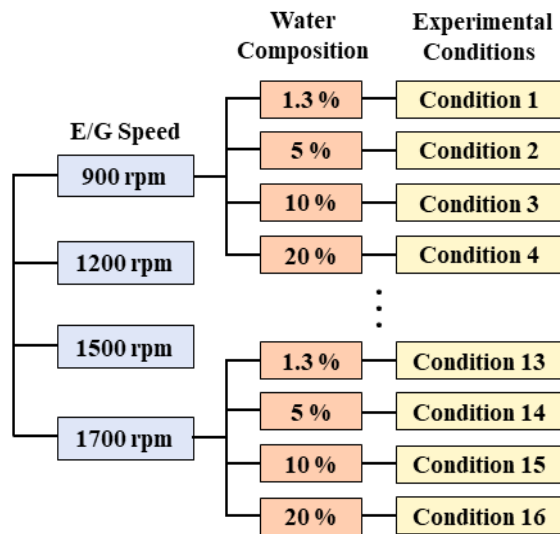Fig. 4 A schematic view of the data collection network



Fig. 5 Experimental conditions

## 4. Experimental Results and Discussion

Prior to transforming the data set collected from the common RPS under each experimental condition to the frequency domain, preprocessing was performed through MIN-MAX normalization to reflect all data on the same level of scale. After preprocessing, FFT was conducted on the common rail pressure data, and the results are shown in Fig. 6.
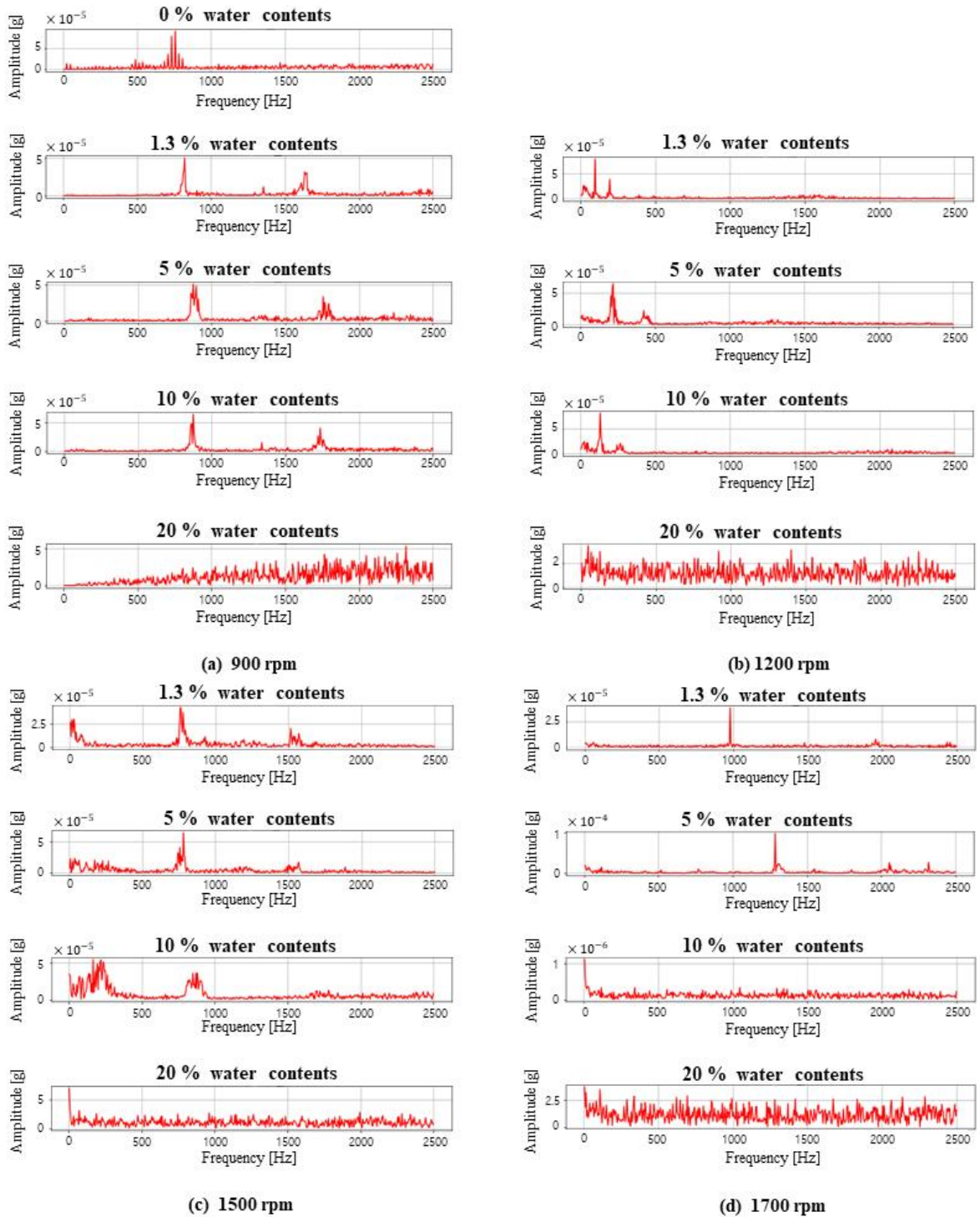
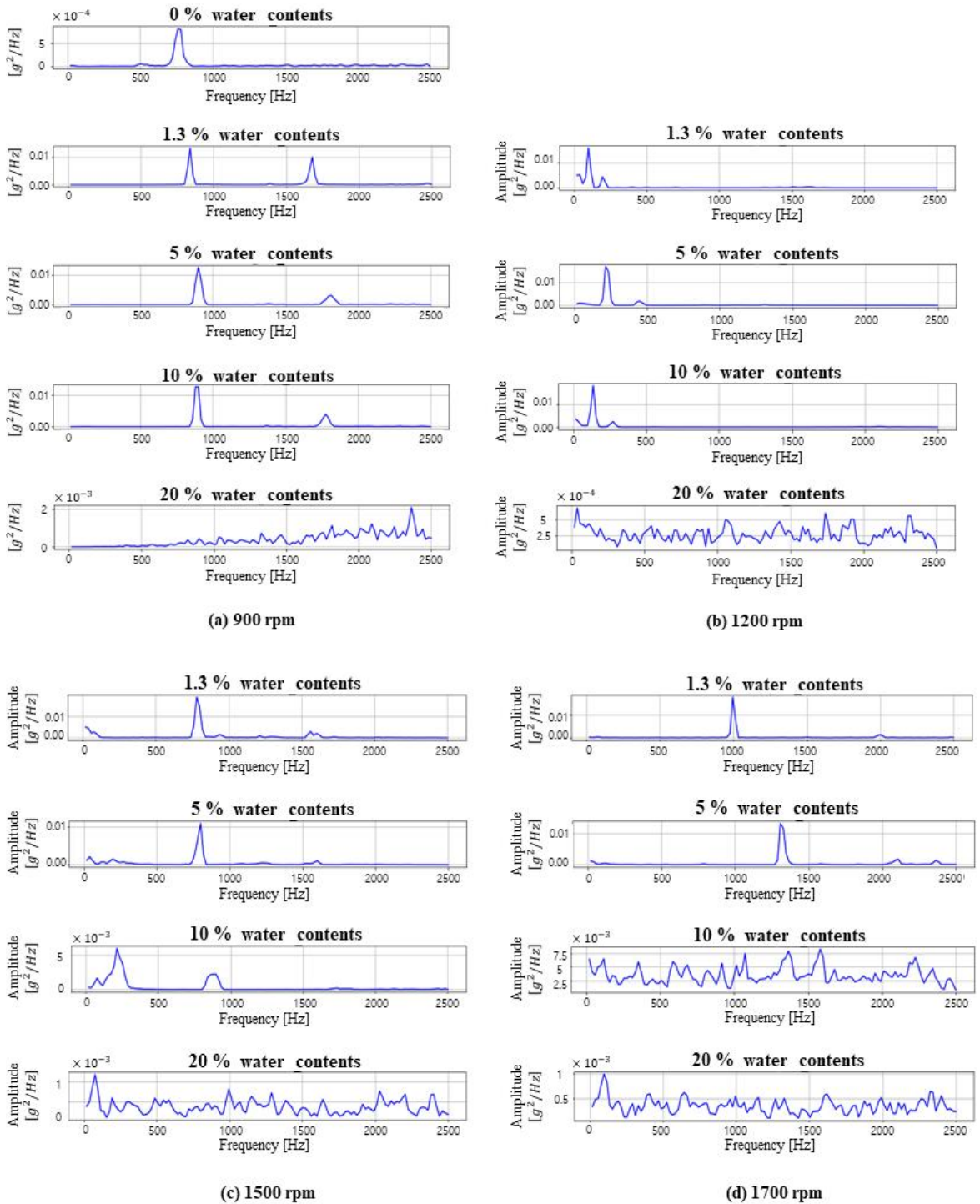**Fig. 6 FFT results based on water contents and rpm**

(a) 900 rpm

(b) 1200 rpm

(c) 1500 rpm

(d) 1700 rpm

Fig. 7 PSD results based on water contents and rpm

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First, under the normal condition of the diesel engine at 900 rpm, a single-frequency component is identified near 750 Hz when using pure diesel fuel (0% water content), as shown in Fig. 6 (a), which can be considered as the intrinsic frequency characteristic of the common rail. However, at the water content of 1.3%–10%, another frequency component is generated between 1,500 Hz and 2,000 Hz, which is attributed to the effect of the water circulation within the diesel engine on the injection system. Moreover, the frequency component distribution varies slightly under the engine revolution speed conditions of 900 rpm, 1,200 rpm, 1,500 rpm, and 1,700 rpm, and the behavioral characteristics of the diesel engine injection system can be determined based on the similarity and variability in the data under different experimental conditions.

Fig. 7 shows the PSD analysis results of the data obtained from the common RPS. There is no significant difference in frequency component distribution up to 5% water content under each engine rotation speed. However, at the engine rotation speed of 1,700 rpm and water content of 10%, the engine injection system began to experience problems due to water in the diesel fuel and formed a frequency distribution similar to that at the water content of 20%, which is considered to be failure data. These results indicate that the timing and conditions for the abnormalities caused by the water in the diesel engine could be determined from the frequency component analysis of the common rail pressure data.

In other words, the diesel engine used in the experiment showed abnormalities in the injection system when the water content in the fuel was 10% or higher, while there was no abnormality in the injection system when the water content was 5% or lower at all engine rotation speeds. As such, a reference value for the water content in diesel fuel can be established for future studies on diagnosis and prediction of diesel engine failures, and the effect of the water content in fuel on the behavior of diesel engine injection systems can be intuitively understood based on the spectrum results.

As a method for comparing the characteristics of the spectrum results transformed using FFT and PSD, a spectral centroid provides a statistical measure on the location of the center of mass in the spectrum and indicates the frequency and size of the spectrum transform, as expressed in Eq. (3) [14].

$$centroid = \frac{\sum_{k=b_1}^{b_2} f_k s_k}{\sum_{k=b_1}^{b_2} s_k} \qquad (3)$$

where, $f_k$ = Frequency in corresponding to bin k

$s_k$ = Spectral value at bin k

$b_1, b_2$ = Band edges in bins

Fig. 8 shows the spectral centroid that compares the average energy of the frequency component at the various engine revolution speeds and water contents. While the average energy was low at the water content of 1.3%–10% and engine revolution speed of 1,500 rpm or lower, it was observed to be high regardless of the engine revolution speed when the water content was 20%, exhibiting an abnormal frequency spectrum due to water damages. However, when the engine revolution speed was higher than 1,500 rpm, the average energy at the water content of 1.3%–10% increased dramatically, reaching the same level as when the engine revolution speed was 1,700 rpm and the water content was 20%. This increase in the average energy of the frequency component indicated the degradation of the injection system performance.

Therefore, while the use of an emulsifier may improve fuel efficiency at a low speed, it can also have a detrimental impact on the injection system of the engine when used at a high speed of 1,500 rpm or higher.

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In the future, studies will be conducted on the diagnosis and prediction of diesel engine failures using the FFT and PSD analysis results on the common rail pressure data.

## 5.  Conclusion

To analyze the effect of the fuel mixed with water on a diesel engine injection system, pressure data from the common rail were transformed to a frequency domain and reviewed. The results obtained are summarized as follows:

1) The behavior of the injection system can be identified through the FFT and PSD analyses of the common rail pressure data.

2) When diesel fuel is mixed with water, the pressure data of the common rail show different frequency component distributions depending on the water content and the engine revolution speed.

3) When the water content exceeds 10% or the engine revolution speed exceeds 1,500 RPM, it may have a detrimental effect on the injection system of the engine.

4) In the future, undertaking studies on the diagnosis and prediction of diesel engine failures using the FFT and PSD analysis results of common rail pressure data will be crucial.

## Acknowledgment

## REFERENCE

1. Cho, J. K., Park, S. J and Hur, K. B., "A Numerical Study on the Operating Characteristics of Natural Gas-Diesel Hybrid in Large-Scale Diesel Engine for Power Generation", Journal of the Korean Institute of Gas, Vol. 19, No. 2, pp. 29-36, 2015.

2. Song, K., "Effect of EGR on power and exhaust emissions in diesel engine," Journal of the Korean Society of Marine Engineering, Vol. 39, No. 9, pp. 870−875, 2015.

3. Park, J. K., Oh, J. M and Lee, K. H., "Combustion Characteristics of MDO and MDO Emulsion in Automotive Diesel Engine," Transactions of the Korean Society of Mechanical Engineers B, Vol. 36, No. 9, pp. 945−951, 2012.

4. Lee, D. G., Roh, H. G and Lee, C. S., "Effect of Diesel-ethanol Blended Fuel on the Vibration and Emission Characteristics in a Diesel Engine," ILASS-KOREA, Vol. 17, No. 1, pp. 1−8, 2012.

5. Lee, C. S., Rosli, B and Kim. J. H., "Effect of Emulsified Fuel in the Engine Performance and Exhaust Emission in the Direct Injection Type Diesel Engine", Journal of the Korean Society of Automotive Engineers's Spring Autumn Conference, pp. 293-298, 1997.

6. Seo, J. W., Park, D. H., "Root cause analysis of the abnormal wear on diesel engine crankpin and lubricant contamination", Journal of the Korean Society of Marine Engineering, Vol. 38, No. 7, pp. 854-867, 2014.

7. Beak, M. Y and Lee, K. S., "Parametric Sensitivity Analysis Using Fourier Transformation", Journal of the Korean Society for Power System Engineering, Vol. 9, No. 4, pp. 58-64, 2005.

8. Shim, K. S., Ahn, H. J., Nam, H. K. and Kim, E. S., "A System Modeling and Controller Design Method Using Discrete Fourier Transform", Journal of the Korean Institute of Illuminating and Electrical Installation Engineers, Vol. 26, No. 2, pp. 34-43, 2012.

9. Walker, J. S., "Fast Fourier Transform, 2nd ed". Boca Raton, FL: CRC Press, 1996

10. Bergland, G. D., "A Guided Tour of the Fast

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Fourier Transform", IEEE Spectrum, Vol. 6, No. 7 pp. 41-52, 1969.

11. Kim, H. H., Park, H. J., Park, Y. D and Choi, J. M., "Introduction to Image Processing Using Fourier Transform and its Applications". Journal of the Science Education in Department of Science, Vol. 38, No. 4, pp.1-11, 2013.

12. Kim, C. W., Kim, C. R., Lee, H. N and Yoo, J. S., "Effects and Limitations of Separating Overlapped Fingerprints Using Fast Fourier Transform," Korean Security Science Review, Vol. 61, pp. 377−400, 2019.

13. Jay Apt, "The spectrum of power from wind turbines", Journal of the Power Sources, Vol. 169, No. 2, pp. 369-374, 2007.

14. Peeters, G., "A Large Set of Audio Features for Sound Description (Similarity and Classification) in the CUIDADO Project." Technical Report; IRCAM, 2004.