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Estimation of Measurement Uncertainty in Electric Vibration Test Equipment

[1]Keun-Seok Park, [1]Chang-Ryoun Son, [1]Jun-Sik Son, [1]Byoung-Nam Kim,
[2]Young-Dal Kim and [2]Dae-Dong Lee
[1]Technology Promotion Center, Research Institute of Medium and Small Shipbuilding,
CO 58415 Yeongam, Republic of Korea
[2]Department of Electrical Engineering, Hanbat National University,
CO 34158 Daejeon, Republic of Korea

Abstract: Equipment including vessels, ships, automobiles and railroad cars where many items of equipment are installed in the limited space, continue to be exposed to special environments such as noise, vibration and shocks, so, they must be tested for their durability, so as to install verified items of equipment to ensure the customer safety and life. However, testers should accurately implement test requirements, so, their accuracy is crucial and laboratories verify tester's accuracy using various methods. This study verified the accuracy of the electric vibration testers designed mainly for testing vibration, using the measurement uncertainty technique.

Key words: Measuring error, measurement uncertainty, vibration measurement, accuracy, laboratories, items

INTRODUCTION

Vessels and ships are equipped with many types of equipment in its limited space. They are continuously exposed to special environments such as noise, vibration and impact due to the mass imbalance in propellers, mechanical vibration of revolving machinery and longitudinal and lateral vibration of propeller shafts. Equipment that can be exposed to special environments characterized by noise and vibration must be evaluated and verified for durability to protect the lives of the passengers and increase the life of the equipment. MIL-STD-167-1A and KS B ISO 10055 are mainly used in the vibration tests of the vessel and ship equipment. The equipment for the vibration tests must accurately meet the requirements of the test method. The measurement values that represent the accuracy of the test equipment, however, contain errors and there is an error range for a true value after considering all the errors that may occur in the measurement. Statistical analysis techniques and evaluation techniques that consider all error-generating factors in judging the reliability of the test equipment are required but they are insufficient (Kim, 2014). Each country adopts the "Guide to the Expression of Uncertainty in Measurement" issued by the International Organization for Standardization (ISO) in 1993 as their standards in measurement uncertainty. Following this guide is recognized as the most appropriate method for uncertainty evaluation and expression today (Huh *et al*., 2010; Lee *et al*., 2012; Son *et al*., 2013; Park *et al*., 2014). In this study, the reliability of the electric vibration test equipment was verified by applying the measurement uncertainty estimation method to the error range of the electric vibration test equipment based on the "Guide to the Expression of Uncertainty in Measurement".

MATERIALS AND METHODS

Measurement uncertainty theory

Measurement uncertainty estimation procedure: Uncertainty is a parameter that represents the dispersion characteristics of the rationally estimated measurement values. Measurement uncertainty is a non-negative parameter that represents the dispersion characteristics of rationally estimated measurement values. It is applied when the result of the report is based on the measurement values (Park *et al*., 2014). Measurement uncertainty is divided into a Type-A standard uncertainty in which uncertainty is obtained by statistically analyzing a series of measurements and a Type-B standard uncertainty in which uncertainty is obtained by using a method other than statistical analysis. When measurement results are obtained by a function that combines different input

Corresponding Author: Dae-Dong Lee, Department of Electrical Engineering, Hanbat National University, CO 34158 Daejeon, Republic of Korea

quantities of various factors, the standard uncertainty of the measurement results is defined as the combined standard uncertainty (Kim, 2014). Extended uncertainty is defined as the combined standard uncertainty multiplied by the inclusion factor k and represents the interval around the measurement results that is expected to include most of the distribution of the rationally estimated measurement values (Lee *et al*., 2012). Figure 1 outlines the measurement uncertainty estimation procedure.

Formulation of a vibration measurement uncertainty estimation model: More accurate measurement uncertainty can be estimated by applying appropriate mathematical models and statistical analysis techniques to various measurement uncertainty factors that affect test results. A model equation with all the factors that generate errors can be established and the effect of each uncertainty factor on the measurement results can be expressed as the positive square root of the sum of the weighted variance and covariance. In this study, the MIL-STD-167-1A Type 1 that is used most frequently in the vessel equipment vibration test was applied. The established model equation is shown in equation. Different test methods may require different amplitudes but the same model equation can be used with the unit adjustment:

$$m = x+\delta y+\delta z \tag{1}$$

- Amplitude (mm or m/sec^2)
- Measured amplitude (mm or m/sec^2)
- Contribution of accelerometer (mm or m/sec^2)
- Contribution of information-gathering equipment (mm or m/sec^2)

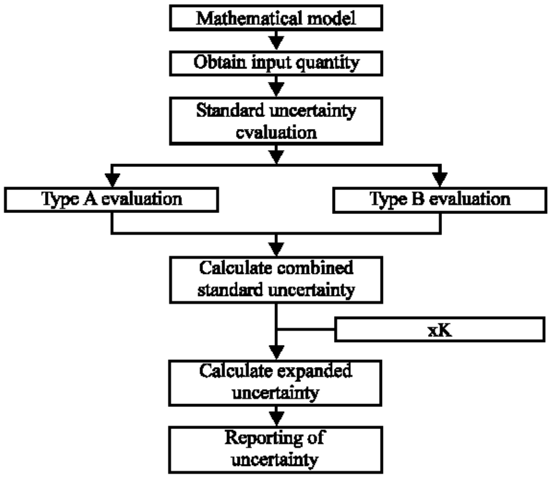

Fig. 1: Flow chart for uncertainty estimation

RESULTS AND DISCUSSION

Vibration test standard uncertainty analysis

Test standards and conditions: MIL-STD-167-1A, type 1 environmental 5.1.2.4.2 exploratory vibration test specifies that the resonance frequency of the test sample must be determined by testing the vibration table in the (0.01±0.002) inch and [(0.254±0.05) mm] amplitude (Son *et al*., 2013). Therefore, the vibration tester must meet the requirements of the standard as closely as possible and must not exceed the allowed error range. The electric vibration test equipment used for the standard uncertainty estimation is shown in Fig. 2.

Type-A evaluation: The type-A evaluation is a method of obtaining uncertainty by using a statistical analysis of the raw data acquired by repeated measurements. It is a method of obtaining uncertainty by statistically analyzing a series of measurements (Kim, 2014). In order to perform the Type-A evaluation, 10 repeated measurements were carried out with the frequency of 4~33 Hz and an amplitude of ±0.254 mm according to the test standard as shown in Fig. 3 and Table 1. The Type-A evaluation was performed according to the results in Table 1 as shown in Table 2.

Type-B evaluation: The Type-B evaluation is a method of obtaining uncertainty by using a method other than the

Table 1: Results of repeated test

No. of repetitions	Measurement results (mm)
1	0.2538
2	0.2542
3	0.2542
4	0.2541
5	0.2536
6	0.2539
7	0.2540
8	0.2536
9	0.2537
10	0.2539

Fig. 2: Electric vibration system

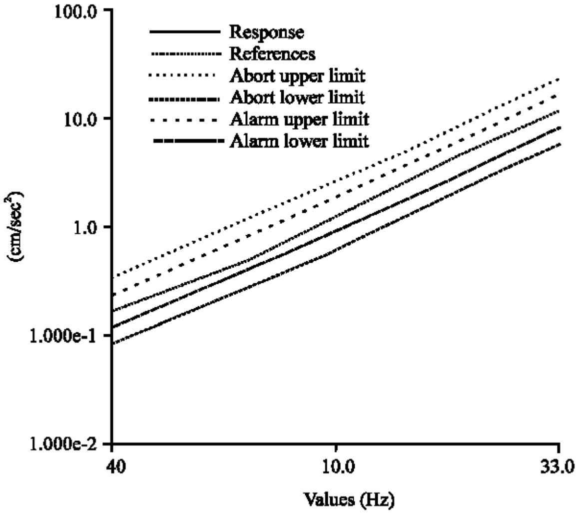

Fig. 3: Test conditions of exploratory vibration

Table 2: Results of type-aestimation

Items	Formula	Analysis (mm)
Average value	$\bar{X} = \frac{(x_1 + x_2 + \Lambda + x_n)}{n} = \frac{1}{n}\sum_{i=1}^{n} x_i$	0.2539
Ktandard deviation	$s = \sqrt{\frac{\sum_{i=1}^{n}(x_{i-}\bar{x})^2}{n-1}}$	2.3E-04
Standard uncertainty	$u(x) = \frac{s}{\sqrt{n}}$	7.1E-05
Degrees of freedom	n-1	9.00

Table 3: Accelerometer information and calibration results

Manufacturer	Model	Serial No.
PCB	333B40	55935
Applied acceleration (m/sec^2, r.m.s)	Sensitivity [mV/(m/sec^2)]	Uncertainty (%) (Confidence level 95%, k = 2)
9.81	52	2

statistical analysis of a series of measurements. It includes the uncertainty specified in the calibration report, the resolution of the test instrument and the uncertainty of the certified reference material (Kim, 2014). The factors relevant to the Type-B evaluation of the electric vibration test equipment include the standard uncertainty of the accelerometer and the standard uncertainty of the resolution of the information-gathering equipment. The accelerometer information used in the test and the uncertainty results specified in the calibration report are shown in Table 3.

Since, the standard uncertainty specified in the calibration report is 2% and the expansion coefficient k is 2, the standard uncertainty of the accelerometer can be calculated by Eq. 2 and the degree of freedom $\mu(y)$ is ∞:

$$u(y) = \frac{0.254}{2} \times \frac{2}{100} = 2.5\text{E-}3\ (\text{mm}) \tag{2}$$

For the electric vibration test equipment, the information-gathering equipment that gathers acceleration sensor information has an information-gathering resolution of 24 bits and its measurement range is ±10V, thus the total range is 20 V. The error voltage (a) of the measurement range as differentiated with the information-gathering resolution can be expressed as Eq. 3. The standard uncertainty of the resolution of the information-gathering equipment can be calculated by converting the calculated error voltage into acceleration and then converting the acceleration into displacement as shown in Eq. 4. The degree of freedom $\mu(z)$ is ∞:

$$a = 20\,\text{V} \div 2^{24} \div 2 \div \sqrt{3} = 3.441\text{E-}7\ (\text{V}) \tag{3}$$

$$u(z) = (3.441\text{E-}7 \times \frac{10^3}{52}) \div (2\pi f)^2 \times 10^3 = 1.0\text{E-}5\ (\text{mm}) \tag{4}$$

Combined standard uncertainty: When measurement results are obtained by a function that combines different input quantities of various factors, the standard uncertainty of the measurement results is called the combined standard uncertainty. As shown in Eq. 5, the combined standard uncertainty $\mu_c(m)$ can be expressed as the positive square root of the sum of the weighted variance and covariance according to the effect of the changes in each input quantity on the measurement results. Applying the standard uncertainty of each uncertainty factor to Eq. 5 yields Eq. 6:

$$u_c(m) = \sqrt{c_1^2 u^2(x) + c_2^2 u^2(y) + c_3^2 u^2(z)} \tag{5}$$

c_i is sensitivitycoefficient, $c_1 = c_2 = c_3 = 1$:

$$u_c(m) = \sqrt{(7.1\text{E-}5)^2 + (2.5\text{E-}3)^2 + (1.0\text{E-}5)^2} = 2.5\text{E-}3\ (\text{mm}) \tag{6}$$

Estimation of extended uncertainty of the vibration test equipment: Extended uncertainty is defined as the interval around the measurement results that is expected to include most of the distribution of the rationally estimated measurement values. Extended uncertainty (U) is expressed with the inclusion factor (k) and the combined standard uncertainty $u_c(m)$ as shown in Eq. 7:

$$U = k \cdot u_c(m) \tag{7}$$

The inclusion factor is a factor that is multiplied by the combined standard uncertainty to obtain extended

Table 4: Analysis of measurement uncertainty

Items	Analysis
Measuring uncertainty	
Std uncertainty	7.1E-5 (mm)
Sensitivity coefficient	1
Degree of freedom	9
Participation ratio	0.079 (%)
Accelerometer uncertainty	
Std uncertainty	2.8E-3 (mm)
Sensitivity coefficient	1
Degree of freedom	8
Participation ratio	99.919 (%)
Resolution uncertainty	
Std uncertainty	3.4E-7 (mm)
Sensitivity coefficient1	1
Degree of freedom	∞
Participation ratio	0.002 (%)
Combined std deviation	2.5E-3 (mm)
Effective d.o.f	1.4E+7
t-value(about 95%)	2
Expanded uncertainty	5.1E-3 (mm)
Measurementuncertainty	0.254 ± 0.005 (mm)

uncertainty. If the correction factor is selected in the t-distribution or if the effective degree of freedom is more than 10, the inclusion factor 2 with about 95% confidence level is applied. The effective degree of freedom is obtained from the Welch-Satterthwaite formula as shown in Eq. 8. In this study, the effective degree of freedom was calculated as being more than 10 from Eq. 8 and the inclusion factor 2 was applied. The extended Uncertainty (U) was calculated as shown in Eq. 9:

$$v_{eff} = \frac{u_c^4(y)}{\sum_{i=1}^{N}\frac{[c_i u(x_i)]^4}{v_i}} = \frac{(2.5E\text{-}3)^4}{\frac{(7.1E\text{-}5)^4}{9}+\frac{(2.5E\text{-}3)^4}{\infty}+\frac{(1.0E\text{-}5)^4}{\infty}} = 1.4E{+}7 \qquad (8)$$

$$U = k\cdot u_c(m) = 2\times(2.5E\text{-}3) = 0.005\ (mm) \qquad (9)$$

Analysis of the measurement uncertainty of the test equipment: The reliability of the test equipment can be verified by the measurement uncertainty estimation technique and the measurement uncertainty is expressed as the measurement value ± extended uncertainty (desired confidence level and inclusion factor). In this study, the measurement uncertainty of the electric vibration test equipment using MIL-STD-167-1A, Type 1 test condition [0.01±0.002 inch (0.254±0.05 mm)] was analyzed as shown in Table 4.

The contribution of the combined uncertainty factor consists of 0.079% of the standard uncertainty of the repeated tests under the same condition, 99.919% of the standard uncertainty of the acceleration sensor and 0.002% of the standard uncertainty of the information-gathering resolution. The standard uncertainty of the acceleration sensor has the widest influence on the combined standard uncertainty, while the standard uncertainty of the information-gathering equipment has a very limited influence. Since, the electric vibration test equipment that tests MIL-STD-167-1A, Type I has an error range of 0.005 mm and an error rate of 2%, compared to the allowed error range of 0.05 mm and allowed error rate of 20%, it can be judged as highly reliable.

CONCLUSION

In this study, the factors affecting the measurement uncertainty of the electric vibration test equipment were investigated by using MIL-STD-167-1A, Type 1 as a measurement uncertainty estimation technique and the model equation was suggested. The uncertainty values were estimated through several tests and the results were analyzed. In the electric vibration test equipment, the sensitivity uncertainty of the control acceleration sensor was considered as the most significant uncertainty factor, thus performing periodic calibration and inspection to improve accuracy will increase the reliability of the test results. Furthermore, the measurement uncertainty estimation technique will be able to verify the error range of the operating test equipment and secure the reliability of the test equipment as one of the methods used in establishing the reliability of the test equipment.

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