Scientific Journal of Gdynia Maritime University

No. 124/22, 7–19
ISSN 2657-6988 (online)
ISSN 2657-5841 (printed)
DOI: 10.26408/124.01

Submitted: 05.07.2022
Accepted: 25.08.2022
Published: 31.12.2022

COMPARISON OF CALCULATING ALGORITHMS FOR LOGARITHMIC DECREMENTS APPLIED TO WELDED JOINT ASSESSMENTS

Adam Szelezinski*[1], Adam Muc[2], Lech Murawski[3], Tomasz Muchowski[4], Marcin Kluczyk[5], Krzysztof Jasiński[6], Romana Antczak-Jarząbska[7]

[1,3,4] Gdynia Maritime University, 81-87 Morska St., 81-225 Gdynia, Poland, Faculty of Maritime Engineering

[2, 6] Gdynia Maritime University, 81-87 Morska St., 81-225 Gdynia, Poland, Faculty of Electrical Engineering

[5] Polish Naval Academy of the Heroes of Westerplatte, 69 Śmidowicza Street, 81-127 Gdynia, Poland, Faculty of Mechanical and Electrical Engineering, m.kluczyk@amw.gdynia.pl, ORCID 0000-0001-7357-6762

[7] WSB University in Gdańsk, 238A Grunwaldzka St., 80-266 Gdańsk, Faculty of Computer Science and New Technologies, rantczak@wsb.gda.pl, ORCID 0000-0002-6853-2041

[1] a.szelezinski@wm.umg.edu.pl, ORCID 0000-0003-2842-0683

[2] a.muc@we.umg.edu.pl, ORCID 0000-0002-9495-087X

[3] l.murawski@wm.umg.edu.pl, ORCID 0000-0003-0089-5492

[4] t.muchowski@wm.umg.edu.pl, ORCID 0000-0002-0200-7041

[6] k.jasinski@we.umg.edu.pl, ORCID 0000-0001-8355-6167

*Corresponding author

Abstract: There are numerous non-destructive methods in welded joints investigation, but the most promising, especially in applications with steady monitoring of the structure, is the vibro-diagnostic approach. In the course of the research work, the responses were obtained and detected by accelerometers, providing valuable diagnostic information, which later was mathematically processed in the field of time or frequency. The mathematical processing aimed to distinguish significant characteristics embedded in the processes typical of the investigated joints and allow an assessment of how they were made. For this purpose, two methods were proposed, based on determining the logarithmic decrement as a function of time. Due to the complicated course of the impact responses, the method of calculating the logarithmic decrement has been suggested, involving the approximation of responses with various functions. According to the research, the analysis of changes in the logarithmic decrement as a function of time applied to welded plates was proposed, as it enables the initial assessment of joint quality.

Keywords: diagnostics, welded joints, non-destructive research, SHM, vibrations, spectral analysis, logarithmic decrement.

1. INTRODUCTION

Among the various modes of transportation, maritime as well as air transport can be exposed to relatively serious risks. Ships often operate in extremely harsh environmental conditions, while marine structures (ships, vessels and offshore structures) are exposed to hostile marine environments for long periods of time. The durability and reliability analysis of offshore structures must consider the interactions of waves and offshore winds (storms) as well as underwater earthquakes for structures with foundations on the ground. The effects of a possible collision, the impact of the corrosive environment and erosion must also be considered.

Welded joints are one of the key elements that must be examined in detail. All welds are tested by measuring techniques, referred to as NDT (non-destructive testing) [Pincu and Kleinberger-Riedrich 2011; Runnemalm 2012; Vospernig, Reiterer and Vill 2013; Onqpeng, Oreta and Hirose 2018]. Non-destructive tests are also known as defect detection techniques. They allow the finding and identifying of defects in material-material structure, like impurities, cracks and irregularities in the internal structure of the material [Muravin 2012; Xin 2012; Findeis, Gryzagorodis and Gerona 2013; Sanchez, Negro and Garcia-Fogeda 2016]. Recently, it has become typical for NDT to use hybrid testing, based on two or more mixed methods. An example of a hybrid method using a similar physical phenomenon is the combination of acoustic emissions and ultrasonic testing [Krause, Dackermann and Jianchun 2015]. NDT is still under development, while new techniques referred to as SHM (Structural Health Monitoring) are still being researched.

Condition monitoring is an interdisciplinary research field aimed at the development and practical application of methods for the detection and monitoring of structural defects and failures by means of a measurement system that is integrated with the device under investigation, operating continuously (on-line) and usually automatically [Alencar et al. 2009; Kohantorabi et al. 2015; Szeleziński, Murawski and Muc 2016; Ohtsu 2016]. Monitoring can be based on a number of sometimes different measurement techniques. In the field of marine applications, the most promising techniques may be methods based on the study of the dynamic characteristics of structures, related to acoustic emissions, "Lamb wave" elastic wave studies by the spectral finite element method, thermal imaging methods, high speed camera imaging, layered studies of electromagnetic properties, comparative vacuum studies or methods based on fibre optic sensors [Lin et al. 2006; Knoeller and Ingold 2010; Kah, Mvola and Suoranta 2014; Szeleziński, Muc and Murawski 2017]. Research into structural monitoring elements, such as defect detection, localization, and identification, has been systematically conducted, but it has often been limited to laboratory and/or preliminary studies [Murawski et al. 2012; Porto, Brusamarello and Azambuja 2013; Aguilar et al. 2016; Muc, Murawski and Szeleziński 2018]. In addition, research in shipbuilding appears to be underdeveloped compared to aviation [Abrantes 2014]. Full monitoring should include completing detection systems, locating and identifying the type of defect with a reliable assumed life cycle for the structure, and evaluating its ability to achieve continuous reliable operation [Keshtgar and Modarres 2013; Jalili, Mousavi and Pirayeshfar 2014].

The shipbuilding industry lacks simplified but reliable mathematical models that could be used to assess the static-dynamic parameters of a ship structure operation (relevant to reliability). The aforementioned models should be applicable to Artificial Intelligence (AI) systems.

It is necessary to evaluate the key measurement elements and the practical selection for such a system. Simplicity and relatively low-cost set monitoring based on vibration techniques appears to be the most promising tool. To date, there has been no practical application of other techniques.

For example, elastic wave testing requires very expensive measurement equipment, such as a 3D laser, which may be difficult to use in the operating conditions of such complex structures as a ship's hull.

The authors of this article are looking for new parameters and characteristics that can be used in non-destructive testing of welded joints. In the first step of analysing the test results, the attenuation spectra were calculated using the FFT method from the recorded response spectrum. Based on the calculated attenuation spectra, the most suitable type of modal hammer head and the optimal impact location on the welded plate were selected.

The next step of the study was to evaluate the dispersion rate of the location and impact force of the modal hammer. Tests were conducted where several attempts were made at a given point with the same head but with different impact force. An evaluation of the impact and spot dispersion effects was made. The resulting responses were obtained as a consequence. An acceptable dispersion was then suggested, for which a spectral analysis of the dynamic characteristics was applied using statistical methods.

It was shown that "free hand" modal hammer strikes can produce repeatable spectra (force and dispersion) at acceptable levels.

The method of analysing the test results is based on the calculation of the logarithmic decrement, which changes over time as the response changes. The research proves that the analysis of the change of the logarithmic decrement over time to welded plates allows the evaluation of the quality and type of weld defects.

In a recent article, the authors supplemented a method for analysing the quality of welded joint workmanship with a description of two algorithms for calculating the logarithmic decrement. The proposed algorithms were consistently applied to real data for welded plates with different weld qualities.

2. TWO ALGORITHMS FOR CALCULATING THE LOGARITHMIC DECREMENT OF WELDED PLATES

As part of the research into welded joints with the vibration method, changes in the construction vibrations amplitude was impacted by the modal hammer. For simultaneous reading, accelerometers were used, placed on the plates according to the scheme presented in Figure 3. The responses obtained may be attributed to a damped oscillating process. The welded joint, which joins the two plates, affects the speed of diagnostic signal loss (speed of energy dissipation), and hence logarithmic decrement analysis may be applied in this case. Logarithmic decrement is widely used to assess the dynamics of multiple mechanical systems. Since the character of the response may be changeable with time, the traditional formula for logarithmic decrement (constant, regardless of time) is not a good choice. In the paper, two figures of logarithmic decrement have been suggested, as presented by formulas (1) and (2). Formula (1) may be applied to determine the averaged damping of the construction in terms of maximal amplitude, while formula (2) may be applied to assess damping changes over time for singular or group vibration periods.

$$\Psi_I = \frac{1}{n} \cdot \ln\left(\frac{A_0}{A_n}\right) \tag{1}$$

$$\Psi_{II} = \frac{1}{n-m} \cdot \ln\left(\frac{A_m}{A_n}\right) \tag{2}$$

where:

ψ – logarithmic decrement,
$A_{0\text{-}n,m}$ – consecutive amlitude values,
n, m – consecutive amplitude number.

On the very stage of implementing formulas (1) and (2) it is clear that the calculating algorithm, based on formula (1) is much simpler than the algorithm stemming from formula (2). In particular, applying formula (2) enables the possibility of calculating the different numbers of periods or their groups. Such a possibility has been verified throughout the research, and the paper's findings have been presented

3. TEST STAND AND MEASURING CONDITIONS

The logarithmic decrements algorithms, expressed by formulas (1) and (2), have been verified for plates with welded joints. For this sake, a laboratory test stand was prepared to check the welded joints using the vibration method (Fig. 1).

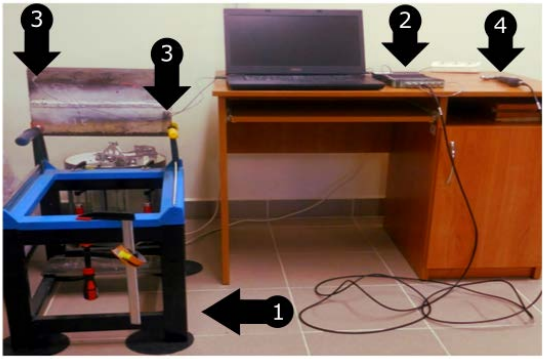

Fig. 1. Test stand for welded joints with the use of vibration methods. The stand comprises: 1 – rack, in which the plates are fitted (welding samples), 2 – vibration analyzer by Bruel & Kjaer, 3 – accelerometers, 4 – a modal hammer with three changeable heads

Source: own study.

The plates have been fitted to the rack in a vertical position for the testing, see Figure 1. Four plates, labelled 0, 2202, 2127 and 2132 have been tested. The plate labelled "0" was the plate with no welded joints, while the three other plates were welded and labelled: 2202 – the plate with no defects, 2127 – the plate with defect type "lack of side fusion", and 2132 – the plate with a simulated crack on the full length of the surface of the sample. All samples with welded joints were tested with the radiography method (Fig. 2) before using them. Radiography testing allowed the preliminary assessment of the welds as well as identifying and localizing the defects in the plates.

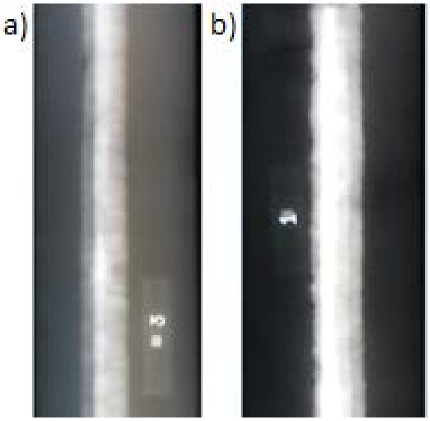

Fig. 2. Radiographic photograph of welded joints, where a) welded plate with no defects in the weld (2202) and b) welded plate with defect type "lack of side fusion"

Source: own study.

The vibrations in the plates were achieved by hammering with a modal hammer with different heads: metal, silicone and teflon. The stroke spots were presented in Figure 3 and marked as: F1, F2 and F3 (Fig. 3).

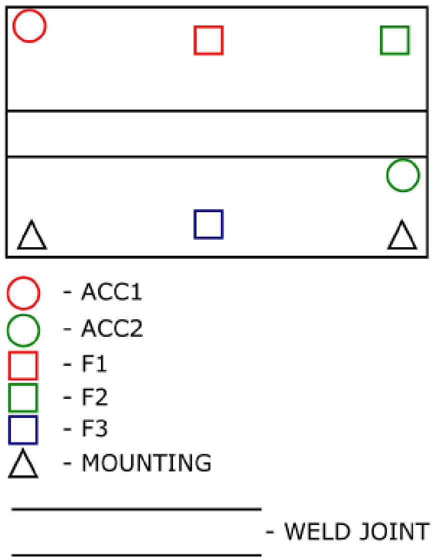

Fig. 3. Schematic diagram showing the arrangement of accelerometers (ACC1, ACC2), points of impact (F1, F2, F3) and plate mounting places in the holders (Δ)

Source: own study.

The results were obtained with the use of accelerometers ACC1 and ACC2. The calculations were done using the measured results obtained using a metal head on the modal hammer.

4. APPROXIMATION OF THE COURSE OF ACCELEROMETER RESPONSES

The oscillation processes of the responses for the welded joints measured using accelerometers may be characterized by an uneven distribution of maximums and minimums.

Variable changes in the vibration velocities and the need to achieve the calculations using a logarithmic decrement led to the urge to investigate the possibility of approximation of the responses with the use of functions, which in their basic form are presented by formula (3). These functions have been comparatively analysed to choose the appropriate approximation function. The analysis shows the correlations between the approximation functions obtained using polynomials of degrees, from two to five, and the exponential function. The results of the work have been presented in the paper (Kah et al. 2014).

$$v_1(t) = \sum_{i=0}^{N} a_i \cdot t^i$$
$$v_2(t) = b \cdot \exp(-c \cdot t) \tag{3}$$

where:

v(t) – approximation function of velocity characteristic,
a_i – i-th constant for the polynomial,
b, c – constants for the exp function.

Figure 4 illustrates an example result of the approximation for responses of the sample with a non-defective weld (this was conducted with the use of a metal head on the modal hammer).

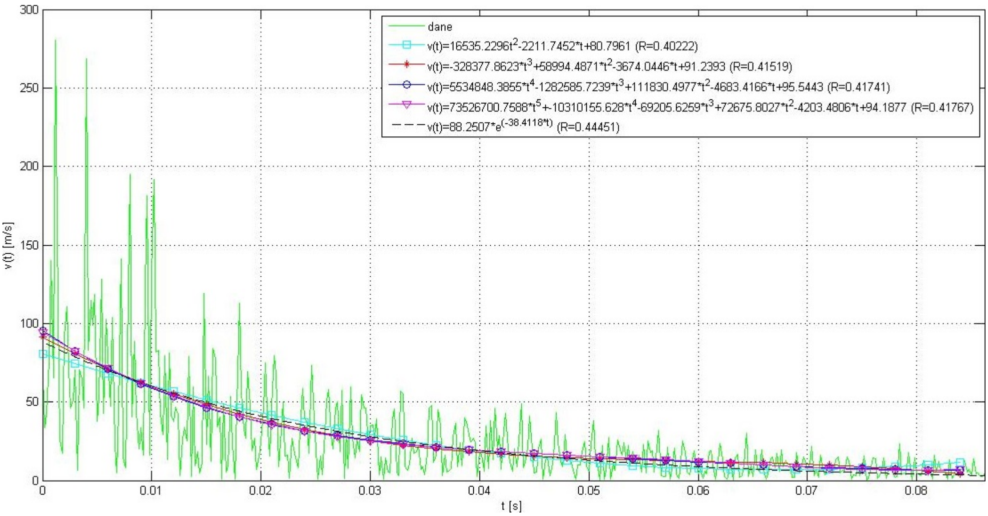

Fig. 4. Example approximation of the responses for the welded plate with the "lack of side fusion" defect with the use of a metal head on the modal hammer (2127)

Source: own study.

Key assumptions for the analysis of the suggested approximation method could indicate that quadric polynomial approximation should not be applied for the given cases since, for small amplitudes, it differs to a significant extent from the actual values of the responses, which consequently increases the approximation error. On the contrary, other functions allow the determination of the approximated response to be satisfactorily. The best results were gained for polynomials of degrees 4 and 5 [Kah, Mvola and Suoranta 2014].

The suitability of the approximation function with real data has been assessed with the R-squared coefficient – the determination coefficient. Its value ranges from 0 to 1, where a value close to 1 means that the approximation function well represents the real data. In contrast, a value close to 0 means the opposite, namely that the approximation function poorly represents the real data. The R-squared coefficient has been used to assess the suitability of approximation functions with real data and allowed a comparison with the applied functions [Kah, Mvola and Suoranta 2014].

5. DISTRIBUTION OF THE LOGARITHMIC DECREMENT FOR WELDED JOINTS

Formulas (1) and (2) have been applied to calculate the logarithmic decrement. The figures present the characteristics of the distribution of the logarithmic decrement calculated with the two formulas in the function involving the number of samples. Figures 5 to 7 show the characteristics of the damping decrement distribution, calculated for two polynomials of the 4th and 5th degree, and these are the first symbols used to mark the individual waveforms. The symbols in the second position refer to the numbers and amplitude values included in the calculations. For digit three, for example, the amplitudes numbered 8 and 11 was taken into account, and for digit 5, numbers 10 and 15. The remaining notations are e – the distribution of the damping decrement obtained from the formula (2) for the approximating function in the exponential form, x4 for the polynomial of degree 4 using equation (1), and x5 for a polynomial of degree 5 using equation (1).

Distribution of the logarithmic decrement calculated for the data obtained in the approximation of the responses with the exponential function has a linear distribution. Such a distribution occurs for the distribution of a logarithmic decrement calculated with the use of both formulas, (1) and (2). Thus, the distribution of the logarithmic decrement calculated for the approximation function with an exponential function has been declared referential and was furthermore used to be compared with the rest of the results.

Figure 5 presents changes in the logarithmic decrement for a single-layer plate with no welded joint with different approximation functions. As it can be seen, for a plate with no welded joint, the given distributions of the logarithmic decrement, stemming both from formulas (1) and (2), are of a linear type. This may testify that damping is even, which can be observable for plates having linear construction characteristics, both structurally and geometrically.

In the case of results obtained for a single-layer plate, it may be observed that there are visible changes for the approximation between the polynomials of the 4th degree (distributions: x4, x4p3 and x4p5) and the polynomials of the 5th degree (distributions: x5, x5p3 and x5p5). No significant changes were observed in the case when formula (2) was applied for calculations for periods 3 and 5, that is distributions denoted x4p3 and x4p5 for the polynomial of the 4th degree as well as x5p3 and x5p5 for the polynomial of the 5th degree.

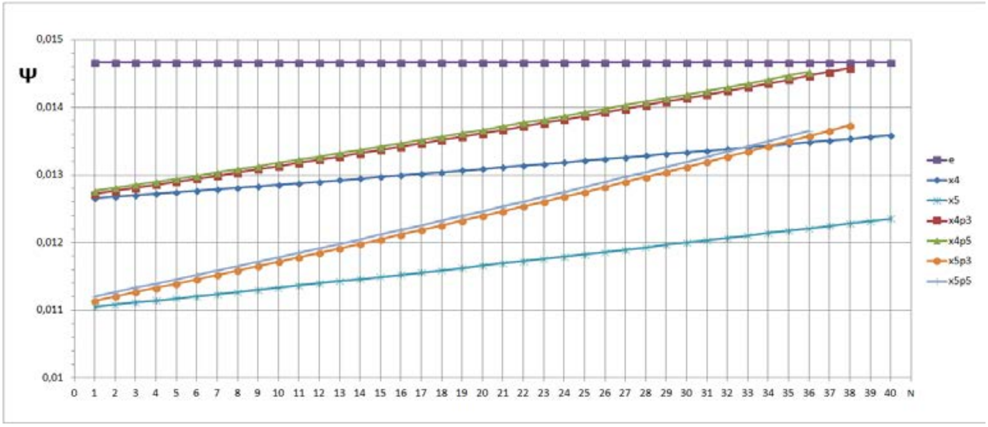

Fig. 5. Distribution of logarithmic decrement for the plate with no weld (0) obtained using two methods

Source: own study.

For the material with a proper weld, the observed damping is to a greater extent variable in time (Fig. 6). This is why the distributions of the logarithmic decrements become curved and converge with the logarithmic decrement made using the exponential function. The intercept point with the referential characteristics of the logarithmic decrement, while formula (1) has been used, is reached at 41 peak amplitudes of response, whereas by using formula (2) the intercept point lowers to 19 peak amplitudes.

In comparing the distributions of logarithmic decrement obtained from formulas 1 and 2, as well as those obtained with formula (2) depending on the number of samples (3 or 5), a change in trend may be observed in the case of the results obtained for a plate with a homogenous material. Figure 6 presents the distributions of logarithmic decrement, proving irrespective of the degree of approximation polynomial (4 or 5), the result is similar to formula (1) or formula (2). Similar convergences may be achieved for formula 2, and a different number of samples (3 and 5) were used. The result may be explained in that a high-quality weld surface has a linear structure characteristic in terms of the material and geometrically. For a well-done weld, the distribution of the logarithmic decrement calculated with formula (1) or (2) gives a similar result, even if the different degree of polynomial or number of periods in formula (2) are assumed.

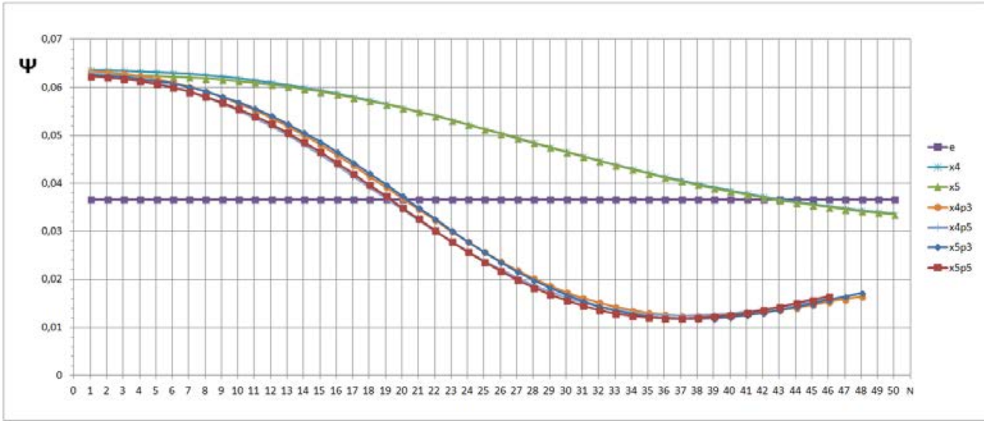

Fig. 6. Distributions of logarithmic decrements for a plate with a high-quality weld (2202) obtained by two methods

Source: own study.

For a welded plate with a lack of any side fusion defect, the effect mentioned above may be even more noticeable. The intercept point with the referential characteristics of the logarithmic decrement with the application of formula (1) has been reached at 31 peak amplitudes of response, whereas using formula (2) means the point is reached at 16 peak amplitudes.

Comparing the distributions of the logarithmic decrements obtained in formulas (1) and (2) and obtained in formula (2) depending on the number of samples (3 or 5) for a plate with a defective weld, another change in the trend may be observed. This was similar to that obtained for the plate with a well-done weld.

Figure 7 presenting the distributions of the logarithmic decrements, shows that irrespective of the degree of the approximation polynomial (4 or 5), the result is similar to the result obtained with formula (1), but different if formula (2) is applied.

In the case that formula (2) is applied and the degree and number of periods of polynomial changed, it may be observed that the distributions oscillate around a number of peaks in amplitudes from 14 to 17. The obtained result may be explained in the way that the low-quality weld surface has non-linear characteristics in terms of both the material and geometrically.

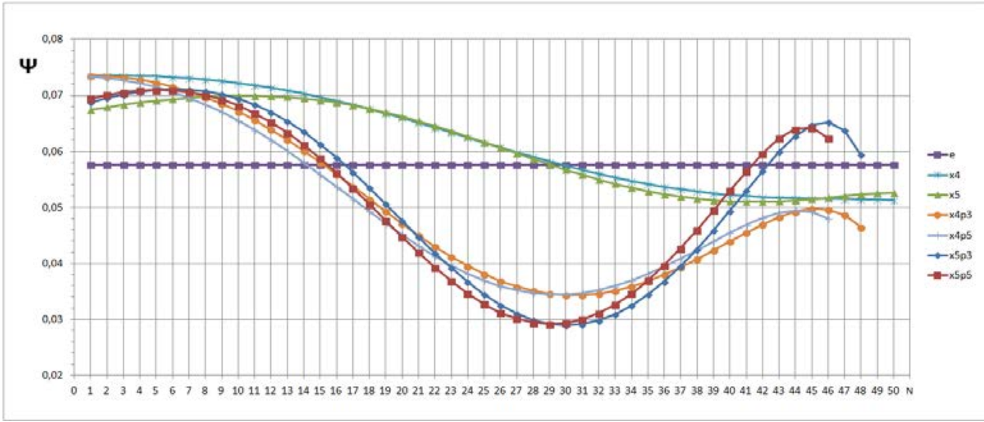

Fig. 7. Distributions of logarithmic decrements for a plate with a lack of side fusion defect (2127) obtained by two methods

Source: own study.

6. CONCLUSIONS

At the moment, the presented method of analysis of responses obtained using welded plates, we can see that vibro-diagnostic testing allows us to assume that detecting weld defects in the autonomous monitoring systems of ships is possible. As expected, for a plate made of one material and deprived of a weld, the distribution of the logarithmic decrement obtained for different approximation functions as well as formulas (1) and (2) is virtually linear. In the rest of the cases, for plates with welded joints, the characteristics of the logarithmic decrement become curved and inclined to intercept with the referential characteristics of the logarithmic decrement. The work shows that the characteristics of logarithmic decrements become curved much faster for plates where the weld is defective.

Applying different functions to approximate responses has allowed their suitability for calculations to be assessed. A comparative analysis of the results for given functions show that a polynomial of 2 degrees should not be used in the calculations. It also appears unjustified to increase the polynomial degree above five since the results remain unchanged. As the characteristics show, applying a 4th degree polynomial allows the obtaining of a satisfactory precision in the distribution of the logarithmic decrement. Comparing two algorithms for calculating the distribution of the logarithmic decrement with formulas (1) and (2) allows us to conclude that the first algorithm enables assessing the weld's quality by analyzing the intercept point of the distribution with the referential one. By applying the second algorithm, and operating likewise, more information about the investigated weld may be obtained, particularly if calculations for two different degrees or numbers of periods of the polynomial are conducted.

REFERENCES

Abrantes, R.F.D., 2014, *Electronic System for Non-Destructive Testing using Eddy Currents Array Probes*, TECNICO LISBOA.

Aguilar, R., Ramirez, E., Haach, V.G., Pando, M.A., 2016, *Vibration-Based Nondestructive Testing as a Practical Tool for Rapid Concrete Quality Control*, Construction and Building Materials.

Alencar, D.A., Silva, S.F., Vieira, A., Soares, A., 2009, *Eddy Current NDT: A Suitable Tool to Measure Oxide Layer Thickness in PWR Fuel Rods*, INAC.

Findeis, D., Gryzagoridis, J., Gerona, L.M., 2013, *Vibration Excitation Methods Applied to Digital Shearography and ESPI. Integration Between a Dynamically Growing Crack with Stuff and Compliant Inclusions Using DIC and High-Speed Photography*, Conference Proceedings of the Society for Experimental Mechanics Series.

Jalili, M.M., Mousavi, S.Y., Pirayeshfar, A.S., 2014, *Flexural Free Vibration as a Non-Destructive Test for Evaluation of Viscoelastic Properties of Polymeric Composites in Bending Direction*, Iranian Polymer Journal.

Kah, P., Mvola, B., Suoranta, R., 2014, *Real Time Non-Destructive Testing Methods of Welding*, Advanced Materials Research.

Keshtgar, A., Modarres, M., 2013, *Detecting Crack Initiation Based on Acoustic Emission*, Chemical Engineering Transactions.

Knoeller, S.L., Ingold, B.J., 2010, *Selecting a Nondestructive Testing Method, Part VII: Acoustic Emission Testing*, AMMTIAC.

Kohantorabi, M., Hossein, M.A., Shahverdi, M., Roohnia, M., 2015, *Vibration Based NDT Methods to Verify Wood Drying Efficiency*, Wood Industry / Drvna Industrija.

Krause, M., Dackermann, U., Jianchun, L., 2015, *Elastic Wave Modes for the Assessment of Structural Timber: Ultrasonic Echo for Building Elements and Guided Waves for Pole and Pile Structures*, Journal of Civil Structural Health Monitoring.

Lin, Y.B., Lai, J.S., Chang, K.C., Li, L.S., 2006, *Flood Scour Monitoring System Using Fibre Bragg Grating Sensors*, Smarter Mater. Struct.

Muc, A., Murawski, L., Szeleziński, A., 2018, *Methods of Cracks Detection in Marine Structures' Welded Joints Based on Signals' Time Waveform Analysis*, Brodogradnja/Shipbilding.

Muravin, B., 2012, *Acoustic Emission Method for Diagnostic and Structural Health Monitoring of Critical Structures During Operation*, HDKBR INFO Magazine.

Murawski, L., Ostachowicz, W., Opoka, S., Mieloszyk, M., Majewska, K., 2012, *Practical Application of Monitoring System Based on Optical Sensors for Marine Constructions*, Key Engineering Materials.

Ohtsu, M., 2016, *Innovative AE and NDT Techniques for On-Site Measurement of Concrete and Masonry Structures*, Springer Netherlands.

Onqpeng, J.M.C., Oreta, A.W.C., Hirose, S., 2018, *Monitoring Damage Using Acoustic Emission Source Location and Computational Geometry in Reinforced Concrete Beams*, MDPI.

Pincu, R., Kleinberger-Riedrich, O., 2011, *Advanced Digital Radiography for Field NDT*, International Symposium on Digital Industrial Radiology and Computed Tomography.

Porto, R.W., Brusamarello, V.J., Azambuja, R., 2013, *Design and Analysis of a GMR Eddy Current probe for NDT*, Seventh International Conference on Sensing Technology.

Runnemalm, A., 2012, *Vibration Induced Disturbances in Automatic Non-destructive Testing*, 18th World Conference on Nondestructive Testing.

Sanchez, P.S., Negro, P.L., Garcia-Fogeda, P., 2016, *Vibration-Based Method for Damage Detection at Welded Beams and Rods*, Latin American Journal of Solids and Structures.

Szeleziński, A., Muc, A., Murawski, L., 2017, *Analysis Concerning Changes of Structure Damping in Welded Joints Diagnostics,* Journal of KONES Powertrain and Transport, European Science Society of Powertrain and Transport Publication.

Szeleziński, A., Murawski, L., Muc, A., 2016, *Analysis of Ability to Detect Defects in Welding Structures with Usage of Dynamic Characteristics Spectrums,* Journal of KONES Powertrain and Transport, European Science Society of Powertrain and Transport Publication.

Vospernig, M., Reiterer, M., Vill, M., 2013, *Simplified Crack Appearance Monitoring at Welded Joints with Strain Gauges,* 6th European Workshop on Structural Health Monitoring.

Xin, L., 2012, *Eddy Current Techniques for Non-destructive Testing of Carbon Fibre Reinforced Plastic (CFRP),* The University of Manchester.