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# ANALYSIS CONCERNING CHANGES OF STRUCTURE DAMPING IN WELDED JOINTS DIAGNOSTICS

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***Abstract***

*Among non-destructive testing methods of welded joints, a vibrodiagnostic method is one of the most promising in applications intended for the continuous monitoring of the structure. The accelerometer-recorded responses provide diagnostic information that requires mathematical processing to extract the essential features typical of the tested welded joints and to evaluate their execution. For this purpose, the proposed method was based on the determination of damping decrement in function of time. Due to the complexity of the responses run, a proposed method consisted of calculating the damping decrement using the response approximation with different functions. It has been shown that the changes analysis of damping decrement applied to welded plates enables the assessment of the quality associated with the weld. Attention was also paid to the elements relevant to the study. This work presents the algorithm and exemplary results obtained from the application of proposed method to several selected sample plates with different type of welds. A scientific apparatus, which purpose was to record dynamic characteristics of welded joints was also described.*

***Keywords***: *diagnostics, welded joints, non-destructive testing, NDT, SHM, vibration, spectrum analysis, damping decrement*

## 1. Introduction

Among various means of transport, maritime transport (beside the air transport) is exposed to relatively highest risk. Seagoing vessels often work under extremely difficult environmental conditions. Moreover, maritime constructions (ships, vessels and the offshore constructions) are exposed to the influence of aggressive marine environment for a very long time. The strength and reliability analysis of maritime constructions have to consider the impact made by waves and wind (storms) including the underwater earthquakes; they have to predict the results of collisions, corrosions, and erosion. Fig. 1 presents the example of disastrous damage (fracture) of a large

*Fig. 1. Container ship fracture as a result of severe weather conditions*

container ship as a result of the very strong stormy weather. This type of structural damage has a catastrophic impact on the safety of the crew, the marine environment, and the ship's cargo.

Each marine vessel and facility works under the supervision of one of the classification societies. They require a detailed periodic safety inspection of the structure from its design to construction. The welded joints are one of the key elements, which undergo precise diagnostic testing. All responsible welds arrested using measurement techniques generally called NDT (Non-Destructive Testing) [2, 3]. Currently, the hybrid tests are becoming the standardized part of NDT. They use mixed approach that combines two or more methods. Hybrid methods are divided into two groups: using the same physical phenomena and acting on the basis of complementary methods of research. An example of a hybrid approach using the same physical phenomenon is the combination of acoustic emission and ultrasound testing. An example of a hybrid approach that is based on acting on the basis of complementary methods of research is surface testing combined with radiographic and/or ultrasonic testing [1, 4]. NDT techniques are well tested, and they give the results, which are sufficiently reliable. However, they have one basic flaw – they are run periodically. In the intervals between tests, the reliability of the structure is uncertain [5]. Particularly in the case of critical events (extremely strong storm, collision, etc.), it is important to note the possibility of further operation of the facility. This information must include the degree of danger of disasters along with the operational parameters, including the time of its safe use. To this end, the new techniques are being developed. They are known as SHM (Structural Health Monitoring).

Structural Health Monitoring is a natural extension of NDT diagnostics of machines and devices. Monitoring is an interdisciplinary research field which aim is development and practical use of methods to detect and monitor the structural damage by the measurement system, which is integrated with the tested device, operating on-line and automatically. Monitoring may be based on the range, often very different, measurement techniques. The most promising techniques in maritime conditions are: methods based on testing of characteristics of dynamic structures, acoustic emission, study of elastic waves of *Lamb Waves* typealong with spectra finite element method, thermovision methods, ultra-fast framing cameras, layered testing of electromagnetic characteristics, vacuum comparative research and the methods based on fibre optic sensors. The aim of SHM systems is to create the measuring and diagnosis system, which would be able to assess the technical condition of the structure continuously and in various environmental and operating conditions. The typical SHM system consists of the net of sensors, which continuously measure condition of the structure and environmental and operating loads. The task of system's central unit is to collect and record measurement signals, analyse them (including selection) and automatically to diagnose occurring risks [6, 7].

Work on the elements of the structure monitoring meaning: detection, localization and identification of damages, are being intensively developed but mostly they are reduced to laboratory and/or preliminary testing. Moreover, shipbuilding works are relatively underdeveloped (e.g. in comparison to aviation). Complete monitoring complements the detection, tracing and fault identification systems by reliable lifetime prediction of the structure and assessments of its further emergency operation. There are no simplistic but reliable mathematical models for static and dynamic evaluation, parameters (reliably relevant for shipbuilding) in marine industry. These models should be able to be used in systems based on artificial intelligence. Evaluation of the key measurement elements and their effective selection for such a system is essential [8].

Monitoring based on vibrodiagnostic techniques is one of the most promising types due to its simplicity and relatively low costs. So far, other techniques do not have practical application. For example, tests which use elastic waves require extremely expensive measuring equipment (e.g. 3D laser) difficult to use in operating conditions for such complex construction as the hull of a ship [9, 10].

## 2. Measurement method and conditions

The test stand to conduct the testing of welded joints using the vibrodiagnostic method was constructed at the Faculty of Marine Engineering at Gdynia Maritime University. The structure of the stand and its most important parts are presented in Fig. 2. The stand includes the holder which can be used to install the plates (welded test pieces) horizontally – 4-point mounting or vertically – 2-point mounting, vibration analyser 3050-A-60 produced by Bruel & Kjaer, two accelerometers 4514-B, modal impact hammer (8206-002) with three interchangeable heads i.e. metal, silicon, and teflon.

*Fig. 2. The test stand for welded joints testing by vibration based methods*

During the process of preliminary tests, the plates were installed horizontally on the holder as it is presented in Fig. 2. The tests were conducted on four plates. The plate marked by number *0* was homogenous and did not have welded joints. The other three included welded plates that were marked by number: 2202 – the plate that did not have any incompatibilities, 2127 – the plate that had incompatibilities in the form of boundary bonding and 2132 – the plate with simulated cracks along the whole length.

All test pieces that have welded joints were tested using the radiographic method before the measurement (Fig. 3). It enabled the assessment of the joints quality along with identification and placement of incompatibilities in the plates.

The measurements of vibration generated by the plates were taken in the prepared test stand. The vibration was caused by the impact hammer with different heads: metal, silicon, and Teflon. The places of strokes are presented in Fig. 4, described by means of *F1*, *F2*, and *F3* (Fig. 4). The results were read by the accelerometers ACC1 and ACC2.

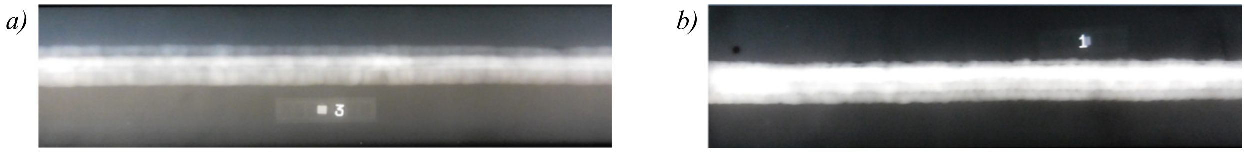

Fig. 3. Radiographic photography of welded joints, where: a) welded joint without faults (2202) and b) welded joint with incompatibility in the form of boundary bonding (2127)

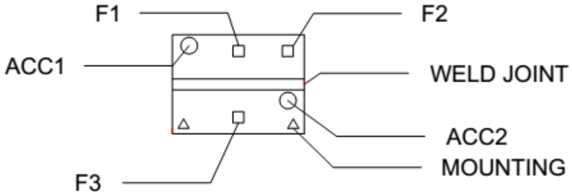


Fig. 4. Schematic diagram showing the arrangement of accelerometers (ACC1, ACC2), places of strokes (F1, F2, F3) and plates mounting places in the holders (Δ)

In the article, the calculations were made for the measurement results obtained using a metal head installed on a modal hammer.

## 3. Damping decrement in welded joints assessment

Using the vibrodiagnostic method in tests on welded joints allows analysing the amplitudes of structure vibrations, in this case, made by modal hammer. While testing, it is possible to record few responses – vibration amplitudes. In order to achieve that, the accelerometers were placed in different location on the tested plate. Recorded responses take the form of damped oscillatory motion. The weld (including its quality), which connects two plates, influences the disappearance speed of diagnostic signal (the speed of energy dissipation), and this is why it is possible to use a damping decrement in its assessment. The dumping decrement is commonly used in assessing the dynamics of many mechanical systems. However, due to the variable nature of response in time, it is impossible to apply regular formula for the logarithmic decrement, expressed as time--independent constant. Two forms of logarithmic decrement were derived in this work and they are represented by formulas 1 and 2. Statement (1) is used to determine averaged structure damping in regard of maximal amplitude; statement (2) is used to assess the damping changes during single vibration periods or its groups.

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

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

where:
$\Psi$ –logarithmic decrement,
$A_{0\text{-}n,m}$ – subsequent amplitude peak values,
$n$, $m$ – subsequent number of amplitude.

## 4. Approximation of response runs from accelerometers

In case of welded joints, damped oscillatory motions of responses recorded by accelerometers are characterized by uneven distribution of maxima and minima. Due to variable changes of vibration speed and the need to calculate damping decrement, the possibility of approximations of response runs was checked using the functions, which are generally represented by formula (3).

In order to choose a proper approximating function, the comparative analysis was conducted, in which the approximations obtained by polynomials from second to fifth degree were collated with an exponential function.

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

where:
$v(t)$ –function approximating the course of speed,
$a_{\text{i}}$ – i-th constant for the polynomial,
$b$, $c$ – constants for the exponential function.

Figures 5 and 6 show the exemplary result of approximations for the response recorded for the sample without faults and the sample with the incompatibility in the form boundary bonding while running the tests using a metal head on the modal hammer.

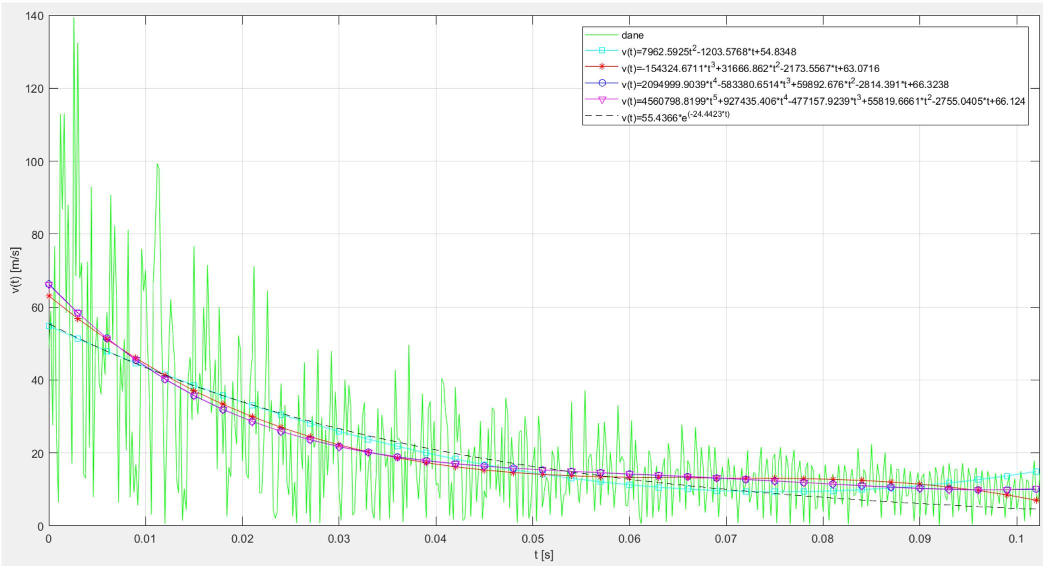


*Fig. 5. Example of approximation of the response received for the welded plate without faults (2202)*

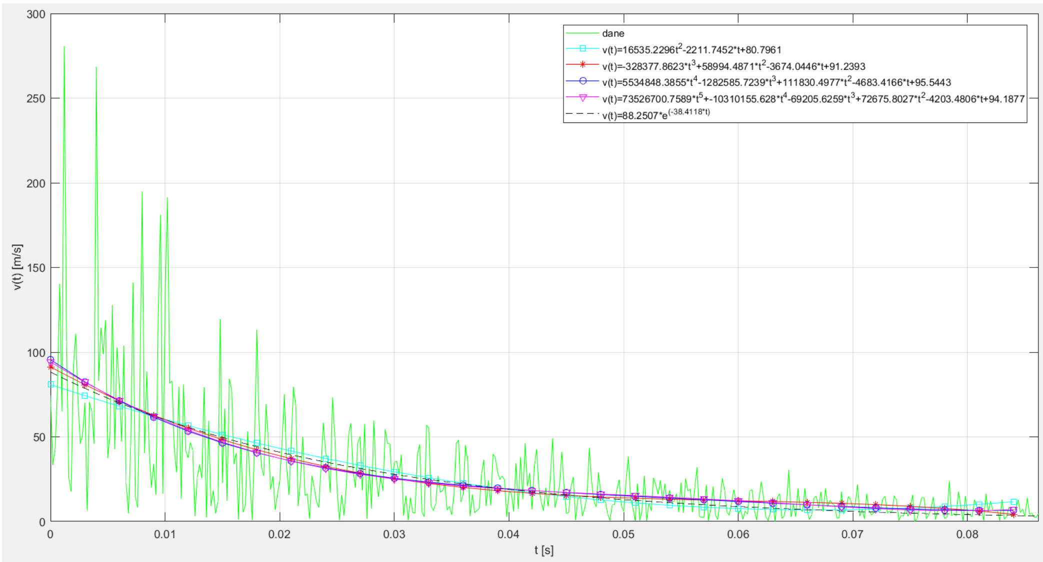


*Fig. 6. Example of approximation of the response received for the welded plate with incompatibility in the form of boundary bonding (2127)*

By verifying the results of the approximation, it may be concluded that the second-degree polynomial is not a proper one in the test case because in regard to small amplitudes it deviates from true values of responses increasing the approximation error. However, the other functions allow determining the approximate response in a satisfactory way. At the same time, it can be noticed that increasing the degree of polynomials above 4 does not improve the approximation of received response.

## 5. Applying the decrement distribution to assessment of welded joints

Dependencies 1 and 2 were used to calculate the damping decrement. The following figures present the results obtained for formula (1). In the near future, however, it is intended to check the validity of the second possibility and obtained results. The first formula allows calculating the decrement distribution in regard of maximal amplitude, and the second one in regard to chosen range.

For the results obtained from each approximating function, the damping decrement was calculated in regard to maximal value ($A_o$). The damping decrement obtained with approximation by exponential function is characterized by linear change. Moreover, it was considered the reference for other results.

Figure 7 shows changes of damping decrement for the homogenous plate without welded joint along the different approximating functions. It is noticeable that the damping decrements distributions determined for the plate without the welded joint represent the constant type. It reflects the uniform damping, which is observable for plates showing characteristics of linear structure both materially and geometrically.

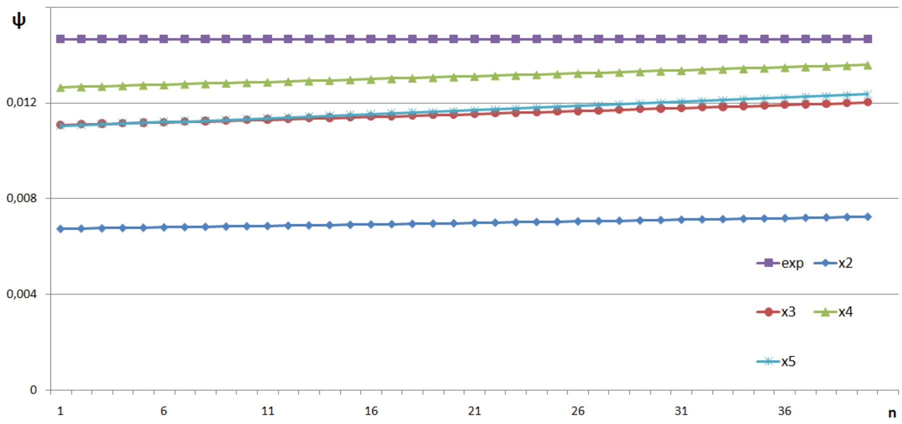


*Fig. 7. Values of damping decrement changes for the plate without weld (0)*

It is possible to observe higher, time-varying damping for material with a good weld (Fig. 8). Therefore, decrements runs are clearly curved and become concurrent with a decrement calculated from exponential function. The intersection with the reference characteristic of the decrement occurs at the 41$^{st}$ peak amplitude of response.

This effect is even more noticeable in case of the welded plate with the incompatibility in the form boundary bonding because the intersection occurred already at the 31$^{st}$ peak amplitude of the response.

## 6. Conclusions

The presented analysis method of the response obtained in the vibrodiagnostic testing of welded plates allows concluding that it will be possible to detect the damages of the welded joint in autonomic maritime structural health monitoring. As expected, for a plate made of one material

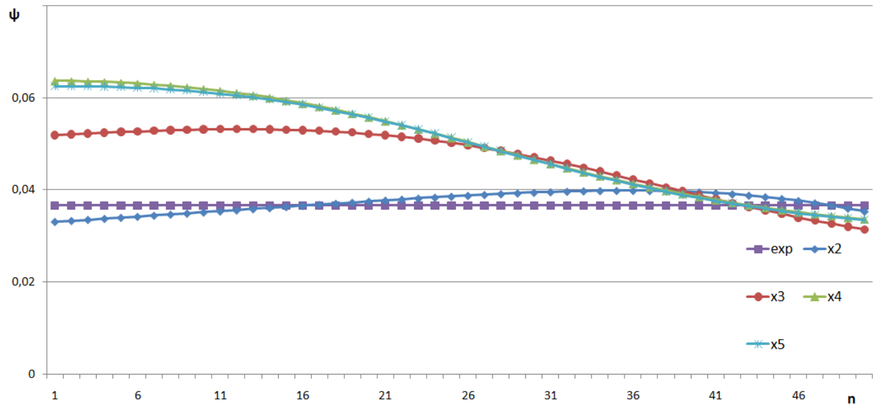


*Fig. 8. Values of damping decrement changes for the plate with a weld without faults on a modal hammer (2202)*

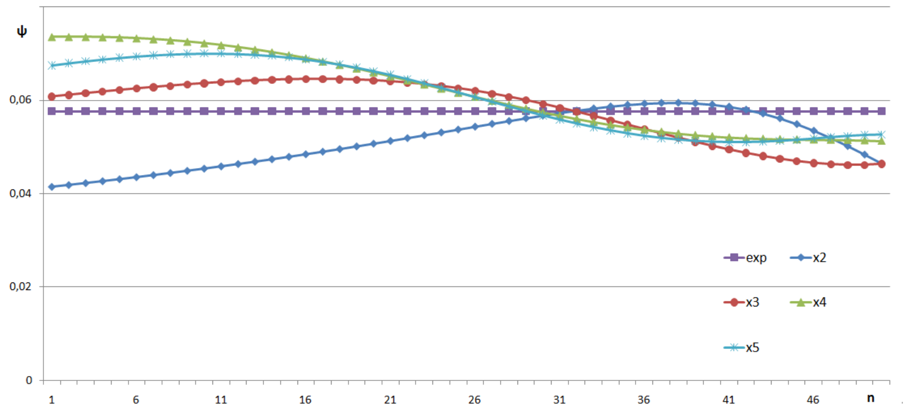


*Fig. 9. Values of damping decrement changes in time for the plate with a weld having the incompatibility in the form boundary bonding (2127)*

and without weld, the damping decrement distribution obtained for different approximating functions is practically linear and parallel to the characteristic of the reference value. In the other cases, i.e. for plates with welded joints, the characteristics of damping decrement clearly curve and tend to intersect with the characteristic of reference decrement of the reference. The results show that the characteristics of damping decrement curve faster for the plates which weld has a fault.

Applying various functions to response approximations allowed assessing their usefulness in concluded calculations. From the comparative analysis of the results obtained for the selected functions, it is clear that the second-degree polynomial should not be used in these calculations. On the other hand, increasing the polynomial above the fourth degree also seems unreasonable as the results overlap. As the characteristics show, using a third-degree polynomial gives an incomplete result that is lower than the result obtained for the fourth-degree polynomial.

Proposed assessment method of welded joints requires further testing on higher number of samples with various faults in welds.

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