Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2018, 56 (128), 41–46
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/312

Received: *17.07.2018*
Accepted: *29.10.2018*
Published: *17.12.2018*

2D and 3D time-frequency dynamic characteristics in the quality assessment of welded joints

Adam Szeleziński[1], Adam Muc[2], Lech Murawski[1]

Gdynia Maritime University, [1] Faculty of Marine Engineering, [2] Faculty of Electrical Engineering
83-87 Morska St., 81-225 Gdynia, Poland
e-mail: {a.szelezinski; l.murawski}@wm.am.gdynia.pl; a.muc@we.am.gdynia.pl
corresponding author

Key words: welding, welded joints, non-destructive testing, NDT, SHM, vibrations, time-frequency characteristics

Abstract

The authors of this article have been looking for new parameters and dynamic characteristics which can be applied to the non-destructive testing of welded joints. All the characteristics have been based on the recorded data generated during the vibration tests of welded joints both with and without failures. This article has dealt with the methods of assessing welded joints using either 2D or 3D time-frequency dynamic characteristics. The calculation procedure that was used for analyzing the simultaneous changes of the response modules, registered by acceleration sensors, has been presented. The vibration amplitudes were transformed into a function of time and frequency (simultaneously) and presented over 2D or 3D time-frequency characteristics. The analyses of the characteristics were performed for a plate without a welded joint, for a plate with a non-defective welded joint and for a plate with a defective welded joint caused by edge bonding. Having analyzed and registered the 2D or 3D time-frequency dynamic characteristics it could be noticed that by presenting the responses, analyzed simultaneously against time and frequency, allowed for the evaluation of whether the examined system maintained non-linearity and, at the same time, allowed for the quality of the welded joint to be indirectly assessed. The proposed measurement parameters of the quality of a welded joint can be defined as a dispersion of the colors from the obtained characteristics. The faults (and the vibration nonlinearity) of the welded joints will be bigger if the dispersion is greater.

Introduction

Among the various means of transportation, maritime transport (as well as air freight) is exposed to relatively serious hazards. Ships often operate in extremely harsh environmental conditions. Additionally, marine constructions (ships, vessels and offshore constructions) are exposed to the harsh marine environment for a prolonged period of time. Analysis of the durability and reliability of marine constructions must involve wave interactions and sea winds (storms) as well as underwater earthquakes. They must also involve the effects of possible collisions, and the effect of the corrosive environment as well as erosion.

Welded joints constitute one of the key elements to be investigated in detail. All the affected welds were tested with measuring techniques referred to as NDT (Non-Destructive Testing) (Findeis, Gryzagoridis & Gerona, 2013; Jajam & Tippur, 2013; Keshtgar & Modarres, 2013; Abrantes, 2014). Non-destructive research is referred to as flaw detection techniques. They allow for the flaws in the structure of materials to be found and identified – material defect – contaminants, cracks, irregularities in the material's internal structure (Alencar et al., 2009; Jalili, Mousavi & Pirayeshfar, 2014; Krause, Dackermann & Li, 2015). Quite recently it has become typical of NDT research to use a hybrid technique, based on mixed methods – two or more. An example of the hybrid method using similar physical phenomenon is the combination of acoustic emission with ultrasound research (Knoeller & Ingold, 2010). NDT research is still in development, resulting in research into new techniques, referred to as SHM (Structural Health Monitoring).

This monitoring is an interdisciplinary field of research with the aim to develop and practically apply the methods of detecting and monitoring construction defects and flaws by a measurement system integrated with the investigated device and operating on an ongoing (on-line) and automatic basis (Pincu & Kleinberger-Riedrich, 2011; Runnemalm, 2012; Kah et al., 2014; Masayasu, 2016). The monitoring may be based on a range of sometimes different measurement techniques. In terms of marine applications, the most promising techniques may be: methods based on investigating the dynamic characteristics of a construction, those connected with acoustic emission, elastic waves "Lamb Waves" research with the spectral finite element method, thermo-vision methods, high-speed imaging cameras, layer research of electromagnetic characteristics, vacuum comparative research, methods based on optical fiber sensors (Lin et al., 2006; Muravin, 2012; Murawski et al., 2012; Onqpeng, Oreta & Hirose, 2018). Research into elements of construction monitoring, such as detecting, localizing and identifying the defects is being steadily conducted, but it has often been confined to laboratory tests and/or preliminary tests (Li, 2012; Vospernig, Reiterer & Vill, 2013; Sanchez, Negro & Garcia-Fogeda, 2016). Moreover, research in the field of shipbuilding seems underdeveloped in comparison to aviation. (Muc, Murawski & Szeleziński, 2018) Full monitoring should include the supplementation of the detection systems, localizing and identifying the type of defect with a credible assumed life cycle of the construction as well as its possibility assessment of further, reliable exploitation (Porto, Brusamarello & Azambuja, 2013; Kohantorabi et al., 2015; Aguilar et al., 2016).

Shipbuilding lacks simplified but credible mathematical models, which could be applied to assess the static-dynamic parameters of the operation of ship construction (vital in terms of reliability). The aforementioned models should be possible to apply in AI systems. It is necessary to assess key measurement elements and their effective choice for such a system. The simplicity and relatively low costs make monitoring based on vibro-diagnostic techniques the most promising tool (Szeleziński, Murawski & Muc, 2016; Szeleziński, Muc & Murawski, 2017). There has been no practical application for the other techniques so far. For instance, elastic waves research requires highly expensive measuring equipment, i.e. a 3-D laser, which may be difficult to use in the operating conditions of such complex constructions as the hull.

The authors of this paper have been searching for new parameters and characteristics, which may be used in the non-destructive testing of welded joints. In the first stage of the analysis of the research results, the authors, based on the recorded spectrum of the responses, have calculated the attenuation spectra with the FFT (Fast Fourier Transform) method. On the basis of the calculated attenuation spectra, the authors have chosen the most appropriate type of modal hammer head as well as the optimal point of impact on the welded plate. The next stage of the research was to assess the rate of dispersion of the impact point and the power of the impact of the modal hammer. To assess both the effects of the impact and dispersion of the impact point, trials have been conducted; during which several strikes were made on the given impact point with the same head, but with a different power for each impact. The responses were consequently obtained (while measuring the coordinates of the hits that were registered). Admissible dispersion was then suggested, to which spectral analysis of the dynamic characteristics was applied using the statistical methods.

It has been proven that hammering with the modal hammer "with a free hand" may bring the repetition of the spectra (power and dispersion) on an acceptable level, which has been described by the authors of the analysis in this paper. In this paper the authors have presented the assumptions of the method of the assessment of welded joints with the use of the analysis of the distribution of the amplitude spectra's mean value, calculated with the method of time windows (statistical measurement in the shape of the mean value as an assumed parameter, of which the analysis of a given welded joint may allow for its quality assessment). The time windows method allows for the simulation of the signal analysis in the field of frequency and time. As the research has shown, the analysis of the distribution of an amplitude spectra's mean value calculated with the method of time windows has proven that the mean values were different in terms of welds, and, at the same time, they determined the quality and defects of the welds connected with them.

Key diagnostic information about the quality of a welded joint was provided by the distribution of the mean values of the spectra obtained from the time windows within the total span of the responses.

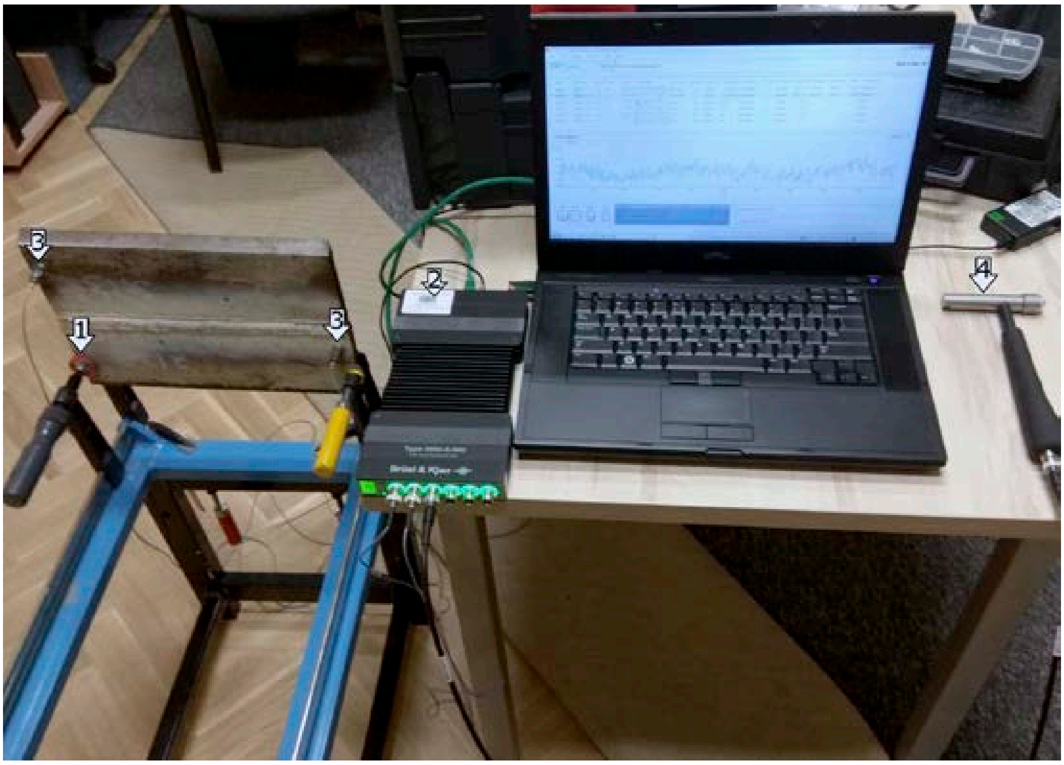


Figure 1. Stand for testing welded joints using vibration methods. The stand includes: 1– rack, in which plates (welding samples) could be mounted horizontally – four-point mounting or vertical – two-point mounting, 2 – Bruel & Kjear type 3050-A-vibration analyzer 60, 3 – accelerometers 4514-B, 4 – modal hammer (8206-002) with three exchangeable tips, i.e. metal, silicon and Teflon

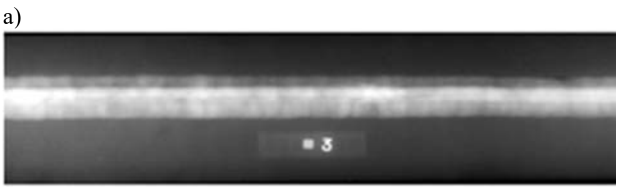
The analysis method of the research results was based on calculating the logarithmic decrement, which changes with time together with the change of the responses, and has been presented in this paper by the authors. The research conducted has proven that the analysis of the change of the logarithmic decrement with time, as applied to welded plates, enables the assessment of the quality and type of defects in a weld. In a recent paper the authors supplemented the method of the quality analysis of the quality of the construction of welded joints by describing two algorithms for calculating the logarithmic decrement. The suggested algorithms were consequently applied to the real data from the welded plates with welds of different quality.

Method and the measurement conditions

The purpose of the conducted work required the construction of a stand which supported the vibro-diagnostic tests on the welded joints (Figure 1). The structure of the test stand and its most important elements has been shown in Figure 1. During the process of the preliminary tests, the plates were installed horizontally in the holder as it has been presented in Figure 1. The tests were conducted on four plates. The plate marked with number 0 was homogenous and did not have any welded joints. The other three included welded plates that were marked with the following numbers: 2202 – the plate did not have any incompatibilities, 2127 – the plate that had incompatibilities in the form of boundary bonding and 2132 – the plate with a simulated crevice along the whole length.

All the test pieces that had welded joints were tested using the radiographic method before measurement (Figure 2). This enabled the assessment of the joint's quality along with the identification and placement of the incompatibilities in the plates.

a)



b)

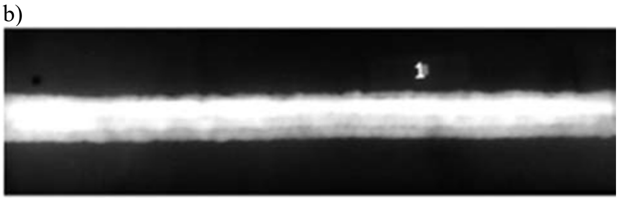


Figure 2. Radiographic photography of the welded joints for a) welded joint without faults (2202) and b) welded joint with incompatibility in the form of boundary bonding (2127)

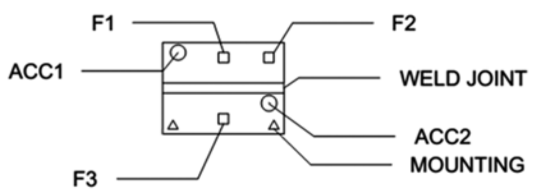


Figure 3. Schematic diagram showing the arrangement of accelerometers (ACC1, ACC2), location of strikes (F1, F2, F3) and the plate's mounting places in the holders (Δ)

The measurement of the vibration generated by the plates was performed in the prepared test stand. The vibration was caused by an impact hammer with different heads: metal, silicon, and Teflon. The places of the strikes have been presented in Figure 3, described by means of F1, F2, and F3. The results were read by the accelerometers ACC1 and ACC2.

Analysis of the 3D time-frequency dynamic characteristics

The complementation of the amplitude-frequency analysis (FFT) presented in the previous articles is its combination with the analysis of the change in the vibration amplitudes in the time domain.

The calculation procedures 1 – 3 were implemented to present the simultaneous changes of the response modules (1) which were recorded by an accelerometer in the time and frequency domain.

(1) $$|X| = g\,(t, f)$$

where:

$|X|$ – vibration module calculated for the accelerometer-registered responses,

t – time,

f – frequency,

$g(t, f)$ – dependency presenting the change of the vibration modules in the time and frequency domain.

By the application of the Cartesian product formula for $t(i)$ and $f(i)$, which represent the discrete time and frequency variable of an analyzed response, the matrixes (2) were calculated. They formed a point net on the TF plane (T – time, F – frequency).

(2) $$(\mathbf{T}(i,j), \mathbf{F}(i,j)) = (t(i), f(j))$$

where:

i, j – number of points of time and frequency,

$\mathbf{T}$. $\mathbf{F}$ – matrixes of time $\mathbf{T}(i,j)$ and frequency $\mathbf{F}(i,j)$ calculated with the use of the Cartesian product formula for $t(i)$ i $f(j)$.

Next, the points of the matrix $\mathbf{FFT}(i,j)$, which represent the spectra of the amplitude vibrations registered by the accelerometer, have been marked on this defined net.

Therefore, the 3D time-frequency dynamic characteristics were the planes drawn in space and defined by the set of points (3).

(3) $$\{\mathbf{T}(i,j), \mathbf{F}(i,j), \mathbf{FFT}(i,j)\}$$

The pcolor function (2D) or surf function (3D) was used to draw the above mentioned planes by the use of the Matlab program. In so doing, the change of the response amplitude in the time and frequency domains was introduced in Figures 4–6, where the change of the response amplitude in the time domain has been marked with a color on an assumptive color scale.

Having analyzed the characteristics presented in Figures 4–6 it could be clearly seen that the presentation of the response in both the time and frequency domains allows for the assessment of whether the tested configuration remained linear and, at the same time, indirectly enabled the estimation of the quality of a welded joint. In this instance, the measurement of the quality of a welded joint may be the dispersion of the colors in the characteristics presented above.

By comparing the characteristics from Figure 4 (a plate without a welded joint) to the characteristics from Figures 5 and 6 (plates with welded joints) it could be noticed that the plate without a welded joint (Figure 4) practically did not contain any dispersion,

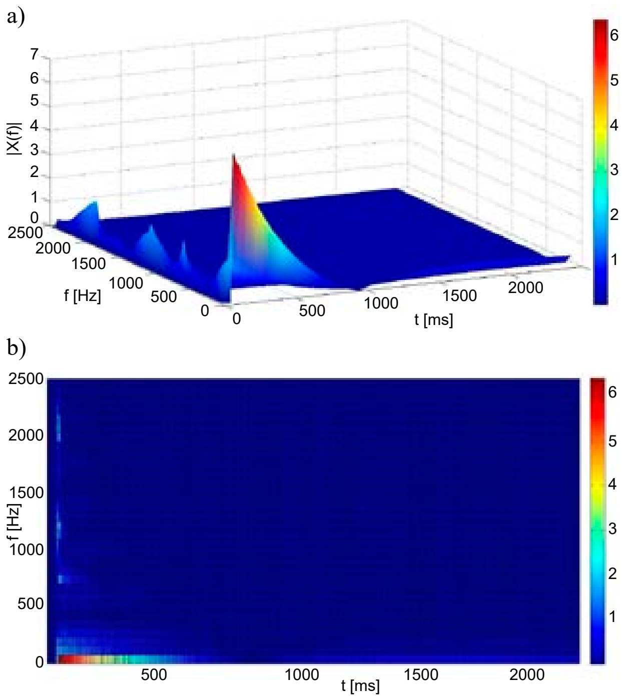


Figure 4. Time-frequency dynamic characteristics (a) 3D and (b) 2D for a plate with no welded joints (0) for an impact made by a modal hammer with a metal head

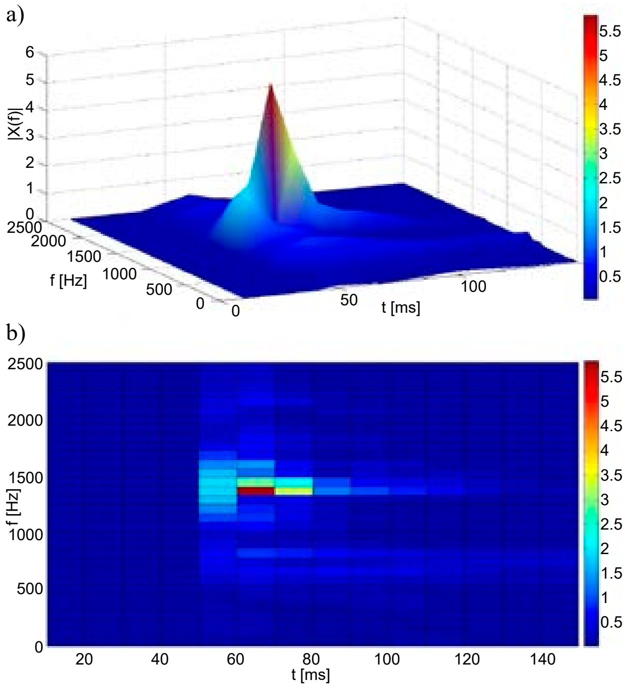


Figure 5. Time-frequency dynamic characteristics (a) 3D and (b) 2D for a welded plate with a non-defective welded joint (2202) for an impact made by an modal hammer with a metal head

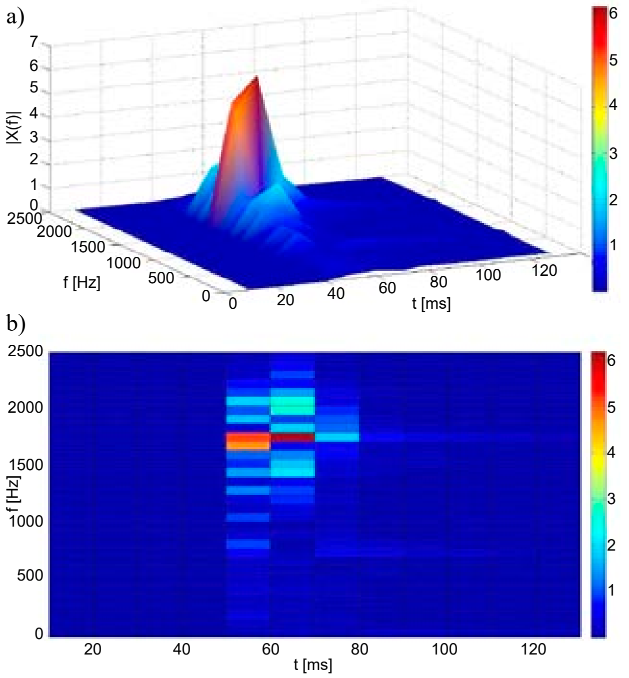


Figure 6. Time-frequency dynamic characteristics (a) 3D and (b) 2D for a welded plate with a fault (lack of side fusion [2127]) for an impact made by an modal hammer with a metal tip

and all the other plates did (Figures 5 and 6). Even the plate with the correct weld (Figure 5) displayed dispersion, therefore each weld, even a high quality one, changed the mechanical properties of the material. However if the quality of the weld was worse, the dispersion was larger, which represents a greater non-linearity compared to the plate with edge bonding (Figure 6).

Conclusions

The diagnostic data acquired as a result of the analysis of the 2D or 3D time-frequency dynamic characteristics allowed for the assessment of the condition and quality of welded joints in addition to other research and elements of their reliability (Bejger & Gawdzińska, 2011; Montewka et al., 2014; Bejger & Drzewieniecki, 2015; Chybowski & Żółkiewski, 2015; Wang et al., 2015; Pulikowski et al., 2017; Yu et al., 2018). Due to the availability of the image processing functions in numerous computational programs, it was possible to apply the proposed 2D or 3D time-frequency dynamic characteristics in order to detect any joint decrements. This could be performed by the use of automatic construction monitoring systems like SHM.

Similarly to the use of the mean value distribution from the time windows for the evaluation of welded joints, the use of time-frequency characteristics allowed for the responses from accelerometers to be analyzed in both the time and frequency domain. In the presented characteristics, the quality of a welded joint could be measured by the dispersion of the colors, which showed additional dissipation and indicated the imperfections of the welded joint, and in the case of a faulty connection, it also allowed for the change in the natural frequency as a function of time to be noticed.

The proposed quality assessment method requires further tests as well as the introduction of a third dimension such as a module variable of the calculated spectral amplitude. Then, apart from applying the data referring to the time-frequency dynamic characteristic, there would be a possibility to also use the information about the intensity of the changes in the amplitude spectra.

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