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Spectral Analysis in Assessment of Multispot Projection Welding

Zastosowanie analizy widmowej do oceny procesu zgrzewania garbowego wielopunktowego

Abstract: The article presents the possibility of an innovative use of spectral analysis to control the quality of joints welded using the multispot projection welding method. The tests discussed in the article included the analysis of welding machine and welding fixtures frequency. The analysis consisted in the impulse-based excitation of vibrations in the entire system (including the welding machine and elements subjected to welding) and the recording of the object response using an acceleration sensor. The results were afterwards subjected to spectral analysis using the Fourier transform. As a result, it was possible to identify the effect of the lack of a weld on the free vibration frequencies of the entire system. Related quality control was performed by comparing the free vibration frequency spectrum of reference elements with that of elements not containing a metallic joint between them. The acquisition and analysis of measurement data were carried out in the LabView environment. The test results confirmed the possibility of using spectral analysis to control the quality of the projection welding process.

Key words: resistance welding, projection welding, quality control, spectral analysis, non-destructive quality control methods

Streszczenie: W artykule przedstawiono możliwość nowatorskiego zastosowania analizy widmowej do kontroli jakości złączy zgrzewanych metodą garbową wielopunktową. Przeprowadzone badania obejmowały analizę częstotliwości drgań własnych zgrzewarki wraz z przyrządem zgrzewalniczym, w którym były zamocowane elementy zgrzewane. Analiza polegała na wzbudzeniu drgań całego układu, obejmującego przyrząd zgrzewalniczy oraz elementy zgrzewane, przez impulsowe wymuszenie oraz rejestrację odpowiedzi obiektu za pomocą czujnika przyspieszenia. Wyniki zostały następnie poddane analizie widmowej z zastosowaniem transformaty Fouriera, co pozwoliło wyznaczyć wpływ braku zgrzeiny na częstotliwości drgań własnych całego układu. Kontrolę jakości zrealizowano przez porównanie spektrum częstotliwości drgań własnych dla detali wzorcowych z detalami, w których nie wystąpiło połączenie metaliczne pomiędzy komponentami. Akwizycję oraz analizę danych pomiarowych prowadzono w środowisku LabView. Uzyskane wyniki badań potwierdziły możliwość zastosowania analizy widmowej do przeprowadzenia kontroli jakości procesu zgrzewania garbowego.

Słowa kluczowe: zgrzewanie oporowe, zgrzewanie garbowe, kontrola jakości, analiza widmowa, nieniszczące metody kontroli jakości

1. Introduction

The projection resistance welding method has been widely used in many industries due to its efficiency, low unit costs and the high quality of joints. The main industrial areas where the method has been used for many years include, among others, the automotive, machinery, electrical engineering and aviation industries as well as the manufacturing of household appliances [1]. An exemplary application of the method includes the joining of nuts with elements made of sheets having thicknesses precluding the obtainment of threaded joints characterised by appropriate mechanical properties [2, 3].

Projection welding equipment and fixtures usually include the following components/elements:

- welding machine provided with a (pressure) force-exerting system with elements enabling the compensation of electrode (pressure) force at individual spots during the settlements of projections and improving process stability [4],
- transformer along with the welding machine control system, enabling the adjustment of the most important process parameters, such as welding time, electrode (pressure) force or welding current stabilisation [5, 6],
- welding machine enabling the stable and repeatable positioning of elements being joined and, at the same time, providing adequate insulation of the support points from the electrical circuit as well as the uninterrupted settlement of projections [7, 8],

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- electrodes supplying electrical energy to the welding area, which, in accordance with the Joule-Lenz law, is transformed into thermal energy making it possible to heat the areas of contact between projections and the base material as well as the obtainment of homogeneous joints between elements subjected to welding [9, 10].

Production practice requires the quality control of welded joints with the primary non-destructive methods of quality control including ultrasonic tests (UT), radiographic tests (RT) and, intensively developed, innovative thermographic methods [10–12]. The above-named methods make it possible to assess the post-weld quality of joints (welds). In turn, a method used in quality assessment based on data recorded during the process is, e.g. the so-called dynamic resistance measurement method [12–14]. The method enables drawing conclusions concerning the course of the process in relation to individual spots or elements, yet results obtainable by means of this method during multi-spot welding turn out to be inexplicit.

The above-presented issues inspired the study aimed to verify the usability of spectral method-based measurements. Such measurements should make it possible to determine frequencies of welding system free vibrations and, consequently, to control the quality of elements made using the multi-spot projection welding method within one fastening.

2. Test methodology

The tests were performed using a prototype welding station enabling the simultaneous joining of up to 4 nuts to a square tube (in terms of cross-section). In addition, the station equipment also enabled measurements of vibrations of elements subjected to welding and the determination of amplitude spectra of measured acceleration signals at selected points of welding machine fixtures.

The test rig was composed of the following elements (Fig. 1):

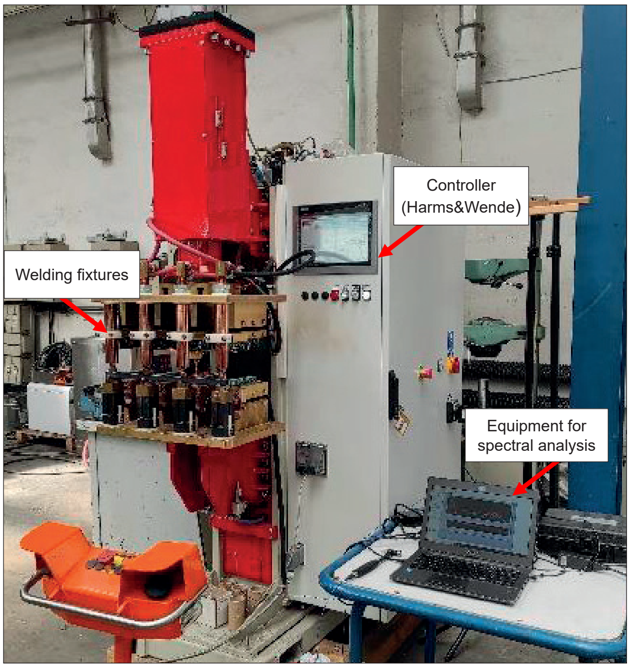


Fig. 1. Projection welding machine (ZGm-350i, ASPA) along with equipment for spectral analysis

- projection welding machine (ZGm-350i, ASPA) featuring a transformer with an inverter and control system (Harms&Wende),
- welding machine pressure-exerting system generating a maximum (pressure) force of 19 kN and a welding system generating a short-circuit current of 49 kA,
- welding fixtures (ASPA) for positioning nuts and tubular sections during the joining process and ensuring the repeatable and stable fixing of components,
- computer supporting the LabView software, enabling the acquisition and processing of signals,
- fixtures necessary for the performance of experimental spectral analysis including a modal hammer, accelerometer and a DAQ device [15–17].

The schematic diagram of the test rig along with the measurement line is presented in Fig. 2.

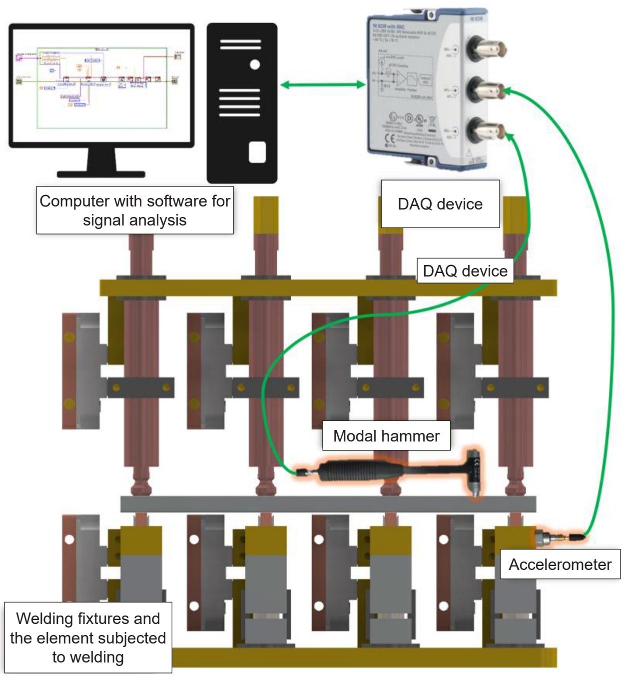


Fig. 2. Schematic diagram of the test rig for spectral analysis

The testing equipment used in the experimental spectral analysis was composed of the following elements:

- computer supporting the LabView software with an implemented algorithm for measurement data. The flowchart of the application developed in the LabView environment along with the measurement part tasked with the acquisition of measurement data from the accelerometer and modal hammer as well as an appropriate functional unit dedicated to spectral analysis are presented in Fig. 3. The DMQmx trigger parameter detected the signal of excitation impulse, initiating the recording of response signals within 10-second time windows (Fig. 3),
- modal hammer (PCB Piezotronics 086C01 – Fig. 4),
- accelerometer (PCB Piezotronics 621C40 – Fig. 5),
- NI-9232 DAQ device (National Instruments – Fig. 6).

The square-shaped (tubular) section used in the tests was made of low-carbon steel; its dimensions being 20 mm × 20 mm × 1.5 mm × 500 mm (length). The projection-welded nuts were M8 (DIN928). During the welding process, the distance between the neighbouring nuts amounted to 150 mm (Fig. 7). Both the section and the nuts were made of steel S235JR. The welding process parameters are presented in Table 1.

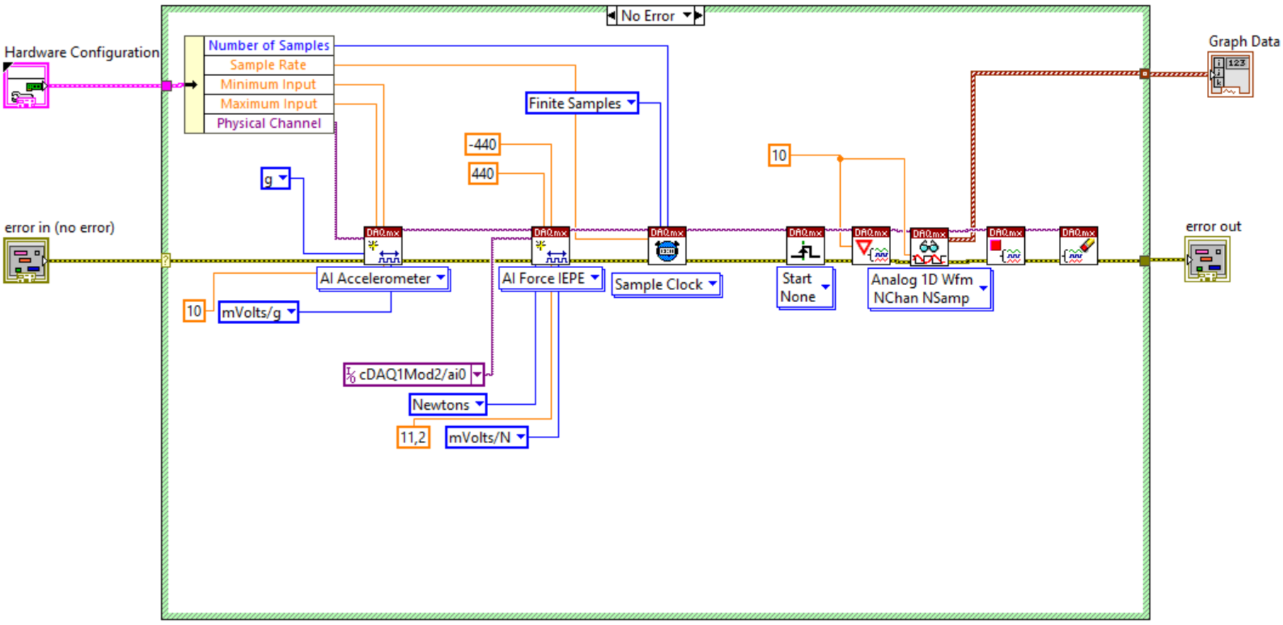
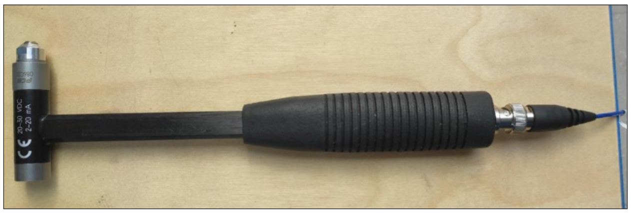
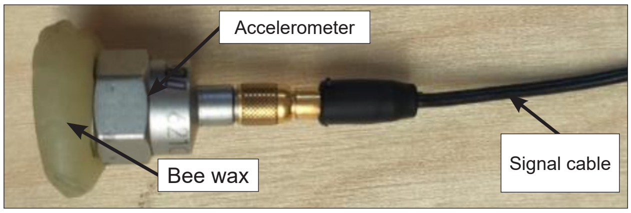


Fig. 3. Flowchart of the measurement part of the spectral analysis software



Sensitivity [mV/N]	Frequency range [kHz]	Measurement range [N]	Resonant frequency [kHz]	Weight [g]
11.2	9.5	440	> 15	100

Fig. 4. Modal hammer (PCB Piezotronics 086C01)



Sensitivity [mV/g]	Frequency range [kHz]	Measurement range [g]	Resonant frequency [kHz]	Weight [g]
10	18	+/- 500	85	4.75

Fig. 5. Accelerometer (PCB Piezotronics 621C40), signal cable and bee wax (fixing the accelerometer)

Wejścia	Częstotliwość próbkowania [kS/s]	Prąd zasilania [mA]
3	102.4	2–20

Fig. 6. DAQ device (National Instruments NI-9232)

Table 1. Welding process parameters

Process parameter	Value	Unit
Current up-slope time	1	[ms]
Current	42	[kA]
Current flow time	240	[ms]
Electrode (pressure) force	1200	[daN]
Number of impulses	1	–

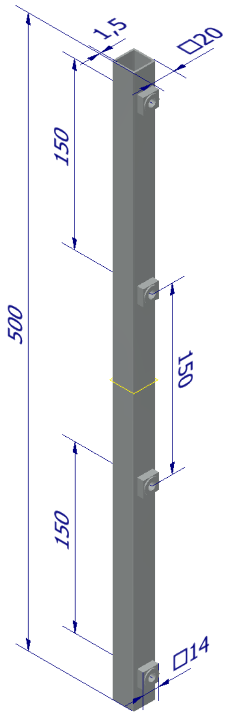


Fig. 7. Square-shaped tubular section with four nuts (M8 DIN928)

The spectral analysis of the elements subjected to welding revealed that, above 5 kHz, the signal was characterized by a high level of noise and did not show any variability features enabling the drawing of conclusions concerning the quality of joints. For this reason, in the remainder of the article, the Authors presented spectral analysis results within the frequency range of 0 kHz to 5 kHz.

The excitation adopted in the tests was an impulse from the modal hammer. During the tests, the element was loaded with a force of 1200 daN, generated by the pressure-exerting system of the welding machine. The accelerometer was attached to the test section in the z-axis direction (Fig. 8). The preliminary tests revealed that, in relation to the tested configuration of the welding equipment, the most explicit results were obtained for the configuration where the accelerometer was placed in the central part of the test element, whereas the modal hammer struck the base of the fourth column in the x-axis direction (Fig. 8). The preliminary tests revealed that the appropriate place for impulse excitation were columns (because of the relatively close location of the joints subjected to the experiment). The accelerometer was fastened using dedicated bee wax as the preliminary tests were characterised by significantly lower noise than that accompanying the use of an electromagnet. The modal hammer had a steel tip (in accordance with the manufacturer's declaration) dedicated to the tested range of recorded frequencies. During the tests, the response signal was not estimated by the value of excitation force recorded by means of the modal hammer. The tests were carried out in accordance with the principles specified in the ISO 7626-5:2019 standard [17].

3. Experimental tests

The test involved the pulsed excitation of the previously indicated spot of the welding fixtures (Fig. 8). The course of impact force changes was measured by means of the signal from the modal hammer. The excitation generated by the modal hammer triggered the vibrations of the entire system (composed of the welding machine, equipment and the element, which was affected by the action of the electrode (pressure) force). The signal recorded in the domain of time was subjected to the Fourier transform, enabling the determination of the necessary amplitude spectra (in the frequency domain) of the response of the test element. [18, 19]. Frequency analysis enabled the determination of the free vibration frequency of the entire system in relation to the (proper) quality of welded joints. The analysis of changes in the free vibration frequency of the system resulting from the lack of joints between some nuts and the square section made it possible to assess the quality of a given element. The tests involved the deliberate making of a series of elements with missing nuts.

The sections with various variants of nuts (welded and not welded to the section) subjected to the tests are presented in Fig. 9.

4. Results of experimental spectral analysis

The test involving the use of spectral analysis in relation to element no. 1 (standard/reference specimen (see Fig. 9)) enabled the recording of the signal amplitude spectrum

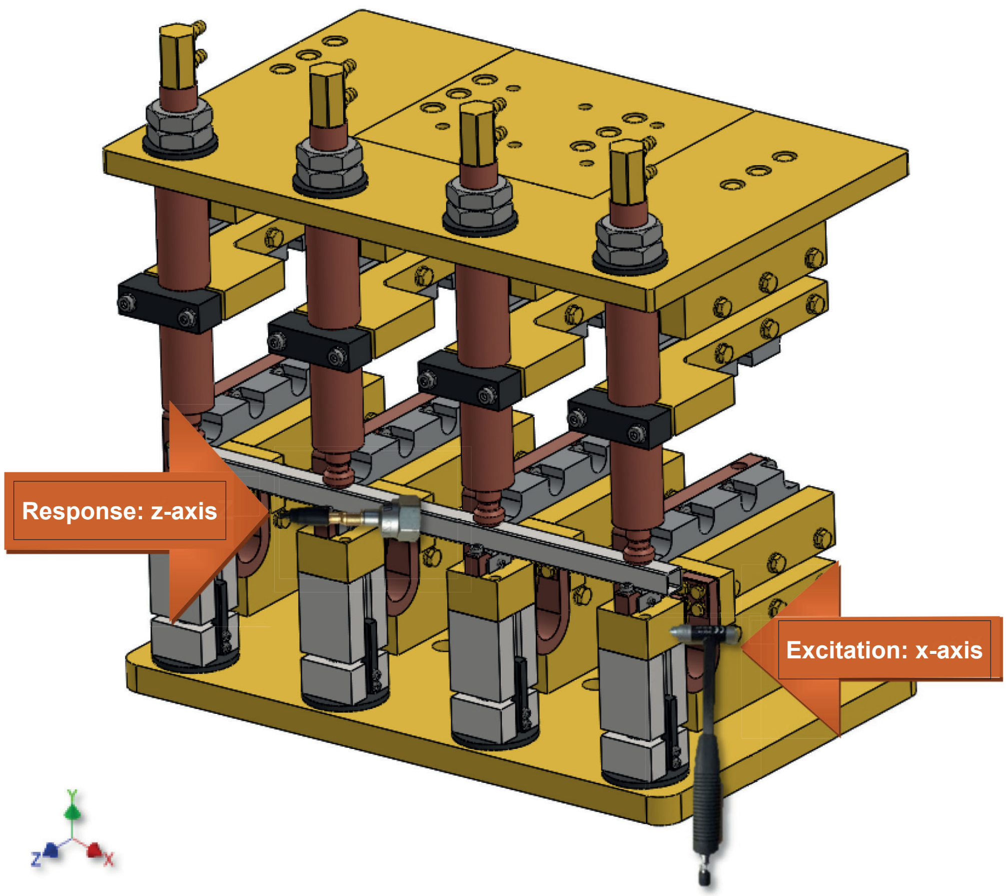


Fig. 8. Fastening of the accelerometer and the system excitation area

Fig. 9. Test specimens: 1 – standard specimen with all nuts welded to the section, 2 – section without nuts (welded to it), 3 – section with nut no. 3 (welded to the section), 4 – section with nuts nos. 1 and 2 (welded to the section), 5 – section with nuts nos. 1 and 4 (welded to the section), 6 – section without nut no. 2 and 7 – section without nut no. 1

curve used as the reference curve for the remaining cases. The test results in relation to individual specimens along with the identified characteristic frequency corresponding to the harmonic component having maximum amplitude Amax are presented in Table 2.

The test results indicated a clearly visible change in the free vibration frequency of the specimens containing imperfections in relation to reference element (standard specimen) no. 1. Based on the foregoing it was possible to analyse the quality of the element. In cases of elements nos. 3, 4 and 6 it was possible to clearly identify additional peak values in relation to a given curve. The presence of additional peak values could enable the identification of the area where the nut had not been welded properly. The frequencies of free vibrations are presented in Fig. 11. Although the identification of the spot of a missing joint based on the comparison of the single value in relation to the highest amplitude of harmonic component was limited, it still made it possible to determine whether all the nuts were welded to a given element. Taking into consideration a greater number of amplitude spectrum components enabled the identification of the majority of cases with respect to the location of a missing joint (nut).

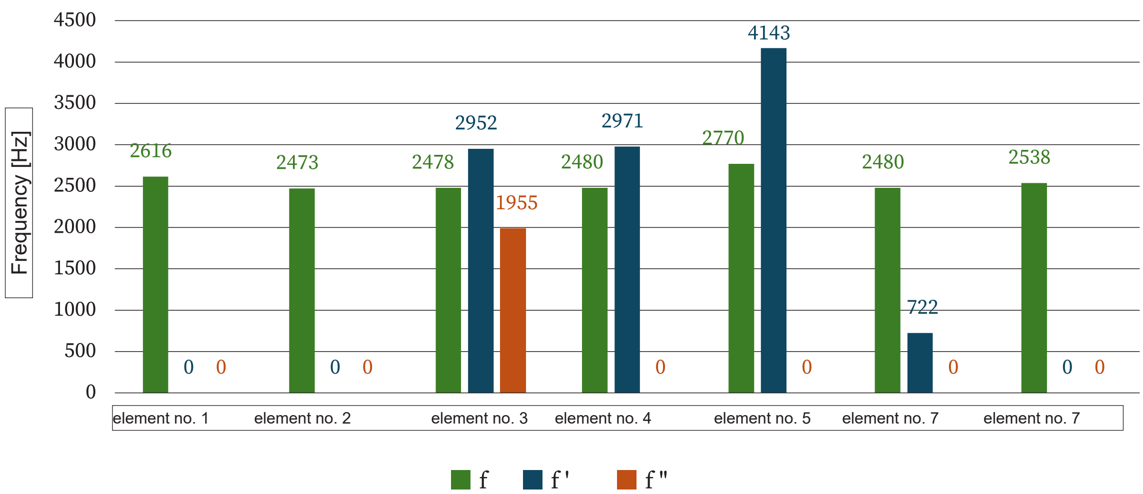
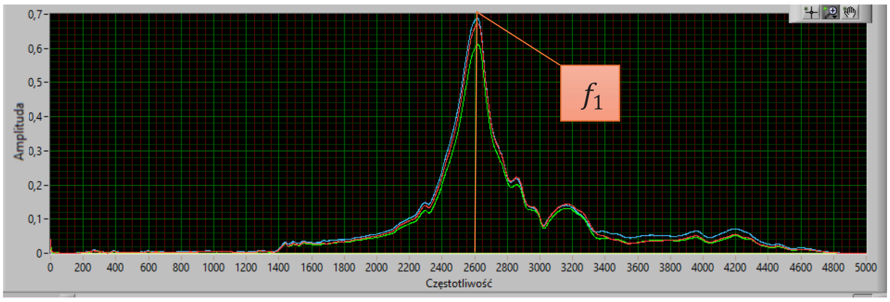
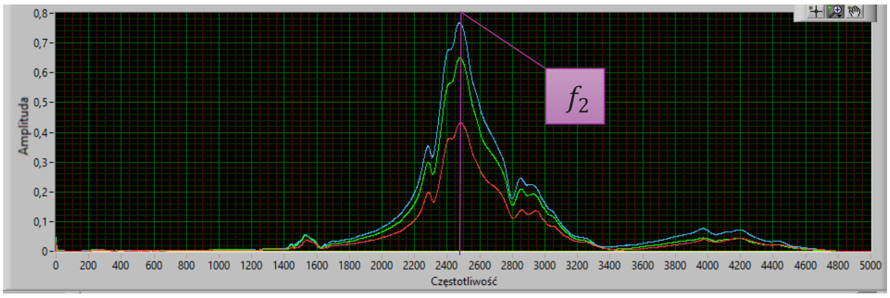
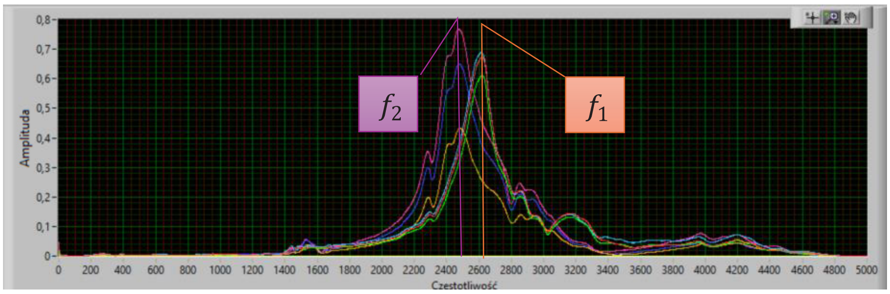


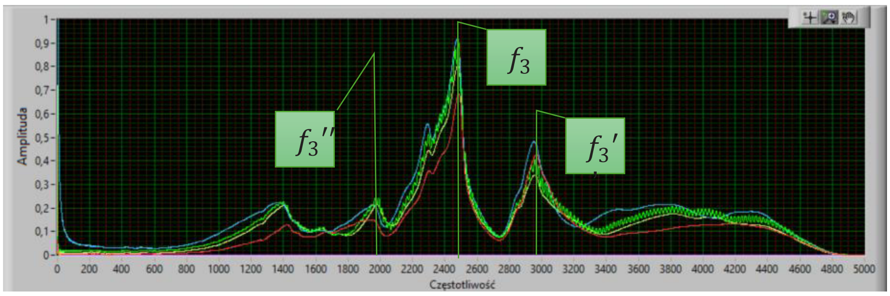
Fig. 10. Bar chart presenting free vibration frequencies in relation to the test elements

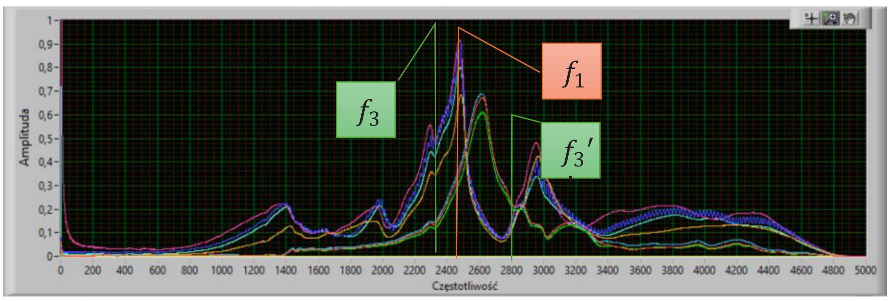
Table 2. Amplitude-frequency curves in relation to individual specimens

<table>
<tr><th>No.</th><th>Frequency for A_{max} [Hz]</th><th>Response signal amplitude spectra [g] in the frequency domain [Hz]</th></tr>
<tr><td>1</td><td>$f_1 = 2616$</td><td>


Element no. 1 – standard (reference) section</td></tr>
<tr><td>2</td><td>$f_2 = 2473$</td><td>


Element no. 2 – section without a nut (welded to it)</td></tr>
<tr><td>1&2</td><td>$f_{1-2} = 2616 - 2473 = 143$</td><td>


Response signal amplitude spectra for elements nos. 1 and 2</td></tr>
<tr><td>3</td><td>$f_3 = 2478$
$f_3' = 2952$
$f_3'' = 1955$</td><td>


Element no. 3 – section with nut no. 3 (welded to it)</td></tr>
<tr><td>1&3</td><td>$f_{1-3} = 2616 - 2478 = 138$</td><td>


Response signal amplitude spectra for elements nos. 1 and 3</td></tr>
</table>

Tablw 2. cont.

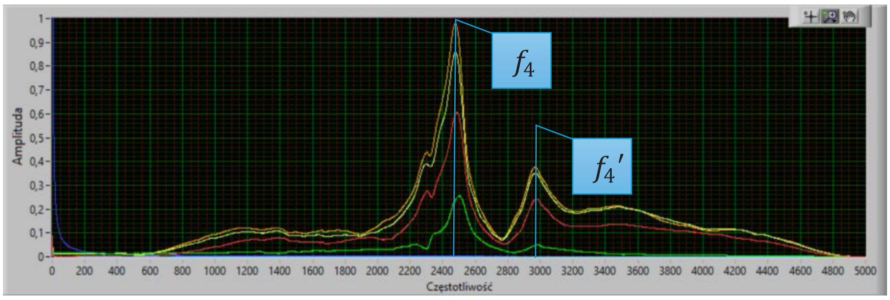
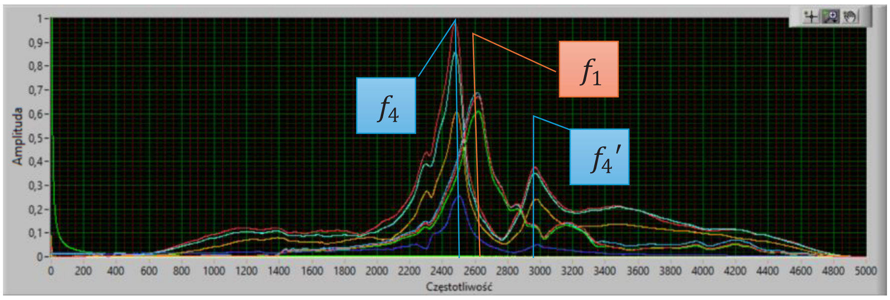
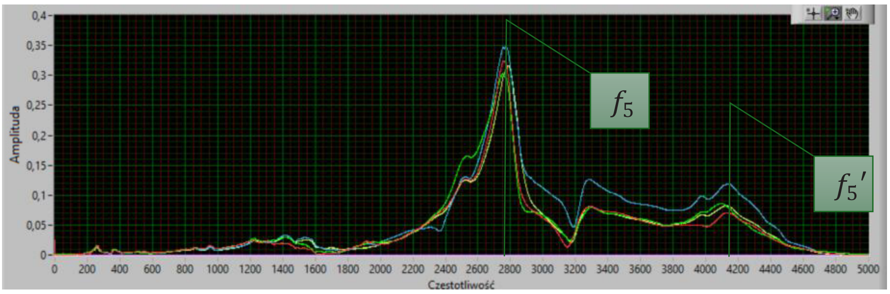
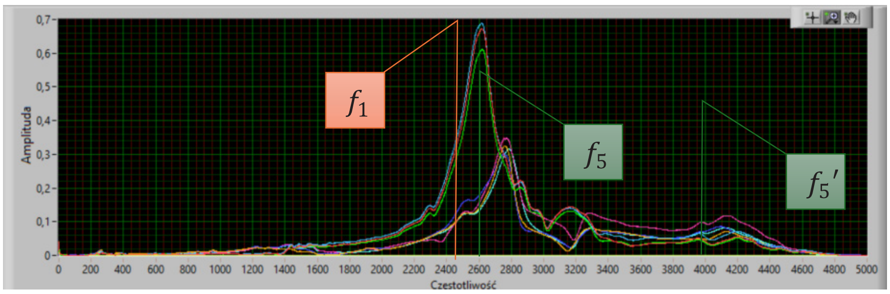
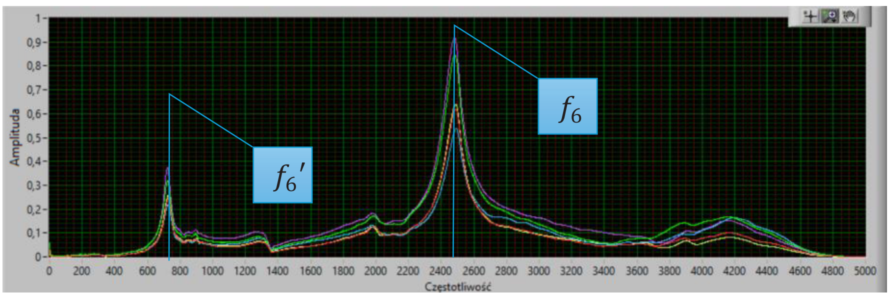
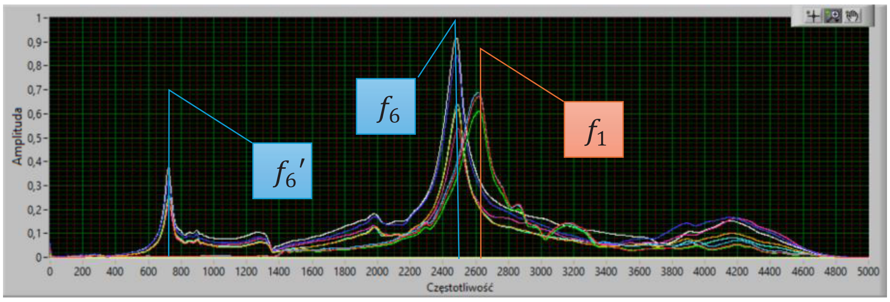
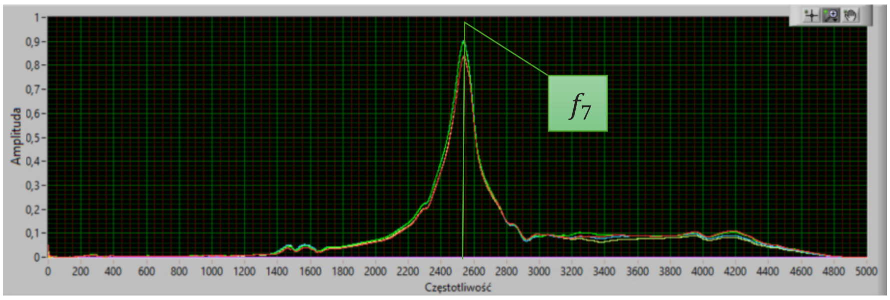
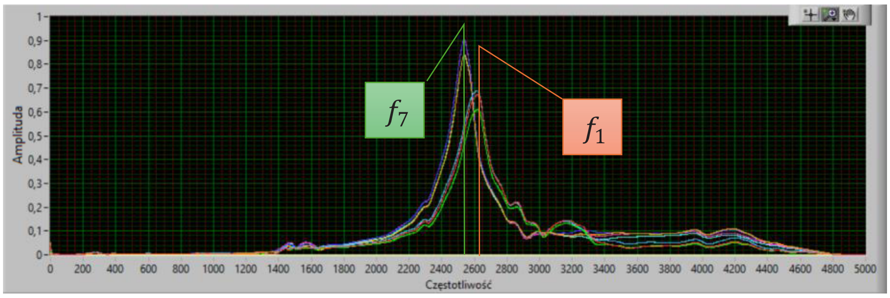
No.	Frequency for A_{max} [Hz]	Response signal amplitude spectra [g] in the frequency domain [Hz]
4	$f_4 = 2480$ $f_4' = 2971$	 Element no. 4 – section with nuts nos. 1 and 2 (welded to it)
1&4	$f_{1-4} = 2616 - 2480 = 136$	 Response signal amplitude spectra for elements nos.1 and 4
5	$f_5 = 2770$ $f_5' = 4143$	 Element no. 5 – section with nuts nos. 1 and 4 (welded to it)
1&5	$f_{1-5} = 2616 - 2770 = -136$	 Element no. 6 – section without nut no. 2
6	$f_6 = 2480$ $f_6' = 722$	 Element no. 6 – section without nut no. 2

Table 2. cont.

No.	Frequency for A_{max} [Hz]	Response signal amplitude spectra [g] in the frequency domain [Hz]
1&6	$f_{1-6} = 2616 - 2480 = 136$	 Response signal amplitude spectra for elements nos. 1 and 6
7	$f_7 = 2538$	 Element no. 7 – section without nut no. 1
1&7	$f_{1-7} = 2616 - 2538 = 78$	 Response signal amplitude spectra for elements nos.1 and 7

5. Conclusions

The above-presented tests and results confirmed the effective usability of spectral analysis in assessing the quality of elements made using the multi-spot projection welding method. The analysis of the test results confirmed the existence of clearly identifiable differences in free vibration frequency values in relation to individual specimens with and without welding imperfections. The method enabled the identification of spots containing joints and those with missing joints.

It is expected that the use of more advanced signal analysis algorithms, e.g. aided by AI (Artificial Intelligence), could increase the effectiveness of the method in the future.

Similarly, the spectral response of the system could provide information concerning the distribution of masses vibrating within the space of the welding system, which, potentially, could be used to control the position of elements subjected to joining, e.g. the verification of the position of the nut in relation to the element, to which the nut is to be welded. The subsequent test stages will involve the analysis of the usability of the above-presented method in the verification of controlling the position of elements subjected to joining.

During the measurements performed using spectral analysis, a significant problem was connected with interference resulting from the quality of impulse excitation, which significantly affected the level of interference in the measured signal and determined the usefulness of the amplitude spectrum. The above-named factors depended on the design of welding fixtures (e.g. stiffness) holding a given element during the welding process and spectral analysis and being capable of dampening vibrations. For this reason, the preliminary tests involved the reduction of system stiffness, which made it possible to reduce the share of the entire station in the amplitude response of the test element, and, consequently, enabled the obtainment of more explicit measurement results.

The above-presented tests demonstrated the practical applicability of spectral analysis in industrial conditions. Further research concerning this issue should take into account the above-presented conclusions. The next stages of research work related to the control system based on spectral analysis should be concerned with the FEM-based confirmation of the results obtained experimentally.

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