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# Vibratory Stabilisation – Constant Development for Industrial Practice

**Abstract:** A welding process leaves behind residual stresses in various areas of elements subjected to welding. Residual stresses affect such operational properties as dimensional accuracy and stability, brittle crack resistance, fatigue resistance, corrosion resistance etc. Vibratory stabilisation is a technological process which may lead to the obtainment of structural dimensional stability of similar efficiency as that of stress relief annealing. The attractiveness of vibratory stabilisation results from its low energy-consuming. The article presents a number of opinions concerning the efficiency of this process (including opinions of the authors dealing with this issue for many years). An important element of this publication is the presentation of the development of technological systems taking place at Instytut Spawalnictwa, e.g. system SW05A (currently produced and implemented in industry). The design of the above named system is based on the state-of-the-art systems of industrial electronics; dedicated software offers extensive customisation.

**Keywords:** vibratory stabilisation, process efficiency, SW05A system,

**DOI:** 10.17729/ebis.2016.1/1

## Introduction

Welding processes leave behind internal stresses in various areas of welded elements. Such stresses affect operating properties including dimensional accuracy and stability, brittle crack resistance, fatigue strength, corrosion resistance etc. In many cases, the obtainment of required operational properties requires the use of additional processes significantly reducing or even eliminating stresses and their effects. Particularly as regards welded structures, a common procedure aimed to eliminate the effects of technological stresses is stress relief annealing. Depending on a material's grade and technical specifications, this process is performed within a temperature range of 550 to 800°C with a hold time ranging from a minimum 2 hours to a time resulting from a specific wall thickness, i.e. even between ten and twenty hours. Stress relief annealing processes often

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consume enormous amounts of energy. Present trends are focused on energy-saving technological processes which could replace previously used methods, including stress relief annealing. Possible solutions include mechanical vibration. As regards costs, technology utilising mechanical vibration aimed to eliminate the effects of technological stresses is very attractive, as possible savings may reach even 90 per cent in comparison with stress relief annealing. The unquestionable economic advantage of this technology is sometimes responsible for its ill-considered or unjustified applications.

## Review of Opinions

A common opinion is that variable stresses resulting from vibratory processes lead to the reduction of technological stresses due to their summation. When summing up, technological stresses and stresses arising from external loads trigger plastic strains reduce the above named stresses. It is worth presenting research results used to confirm this thesis. Early research concerning this issue revealed that variable stresses can affect the size of welding stresses, provided that their sum triggers appropriate plastic strains. The formation of plastic strains is favoured by the susceptibility of steel to plastic strains when subjected to variable stresses (the appearance of the so-called cyclical yield point, i.e. lower than a yield point accompanying the exposure to static loads) [1, 2]. It should be noted that experiments described in publications referred to above were performed consistent with directions of welding stresses and stresses resulting from external loads. Therefore, practically, the reduction of welding stresses takes place when amplitudes of variable loads are appropriately high. Publication [3] presents test results concerned with the effect of variable vibration-triggered stresses on technological stresses caused by cold work. Also, in this case the possibility of reducing technological stresses (of 350 MPa), yet with significant amplitudes of variable stresses (between 250 and 420 MPa), was confirmed. It was also observed that the number of load cycles affected the reduction of technological stresses. Further publications, based on the previously presented thesis, focus on specific practical applications where electromechanical vibrators were used as sources of variable loads. Specific examples were discussed using the notion of Vibratory Stress Relief (VSR). However, the publications raised some doubts, among others, because of the lack of measurement results concerning welding stresses after performing VSR or due to a failure to provide values of amplitudes of variable stresses generated using vibratory devices [4]. Other experiments were performed on elements made of austenitic steel 314L having a yield point of $R_e$ = 320 MPa. These experiments were performed as tests concerning applications of vibratory processes for stress relief of a welded structure being a component of a Tokamak system (i.e. a system used for nuclear physics research) [5]. Technological stresses were introduced by remelting flat test specimens. The specimens were used to determine the dependences of reductions of technological stresses on amplitudes of variable stresses and the number of cycles. Also in this case, the thesis about the dependence of the reduction of technological stresses on the amplitude of variable loads was confirmed. In addition, it was possible to observe a dependence between strains of a test element subjected to variable force loads and the number of cycles (explained through the phenomenon of creeping). The test results were used for the stress relief of the base of a Tokamak structure, i.e. a disk made of steel 314L having a diameter of 7600 mm, thickness of 70 mm and a weight of 34 tons, as a welded structure. The stress relief was performed at a frequency of 48 and 61 Hz for approximately 15 min. Measured amplitudes of variable stresses amounted to 18 MPa, whereas the reduction amounted to approximately 39.5 MPa for the initial value of welding stresses amounting to 295 MPa.

Welding stresses were measured using two methods, i.e. the X-ray method and the pinhole method, which raised some doubts, as the use of the pinhole method requires very careful preparation of the measurement surface by removing, among others, excess weld metals. It is very likely that the removal of an excess weld metal alone, and not the vibratory process, might have led to the presented decrease in welding stresses. It should be emphasized that, according to the article, before the vibratory process, the stresses were measured using the X-ray method. As practice proves, stress result measurements performed using different methods are usually divergent and their application without reliable validation is risky. The effectiveness of vibratory stress relief presented in publication [6] also raised reasonable doubts. The test involved welds made of toughened steel D6AC ($R_{0.2} = 1345$ MPa, $R_m = 1931$ MPa, A5 = 7%). The determined reduction of welding stresses was restricted within a range of 0 to 25 MPa. However, the publication did not mention at what amplitudes of variable stresses the stress relief process was performed. The degree of reduction was, in fact, restricted within the scatter of measurement method accuracy (x-ray method). Therefore, it was unjustified to unequivocally claim that the reduction of technological (welding) stresses had taken place.

The tests also involved attempted vibratory stress relief [7, 8, 9] performed using the Finite Element Method. FEM was applied for modelling the effect of vibration-triggered dynamic forces on elements containing technological stresses caused by thermal or welding processes. The effect of vibration-triggered mechanical loads on the size of technological stresses was confirmed. At the same time, it was determined that the degree of technological stress reduction was strictly dependent on the amplitudes of dynamic stresses. The tests concerning the effect of vibratory processes on the mechanical properties of steel structures demonstrated that dynamic forces responsible for the reduction to 0.5 of the yield point did not reduce the fatigue strength of the above named structures [10].

The practical application of a technology utilising mechanical vibration entails the necessity of confirming its effectiveness. It should be taken into consideration that a process may not leave any visible signs, e.g. scale in the case of stress relief annealing. Measurements of technological stresses are practically out of question as they are destructive, whereas non-destructive methods are very costly and validation is highly problematic or even impossible. Therefore, a vibratory process is performed for detected resonant frequencies, and thus for maximum responses of an element. Depending on the technique applied and the producer of a system, the tuning of resonant properties takes place in various manners. It is assumed that the reduction of welding stresses is manifested by a change consisting in an increase in the value of acceleration in the state of resonance and a decrease in resonant frequency (see Fig. 1).

Publications [11, 12] contain an analytical description of the effect of a vibratory process on changes of parameters (vibration frequency and power of a vibrator). The course of parameters

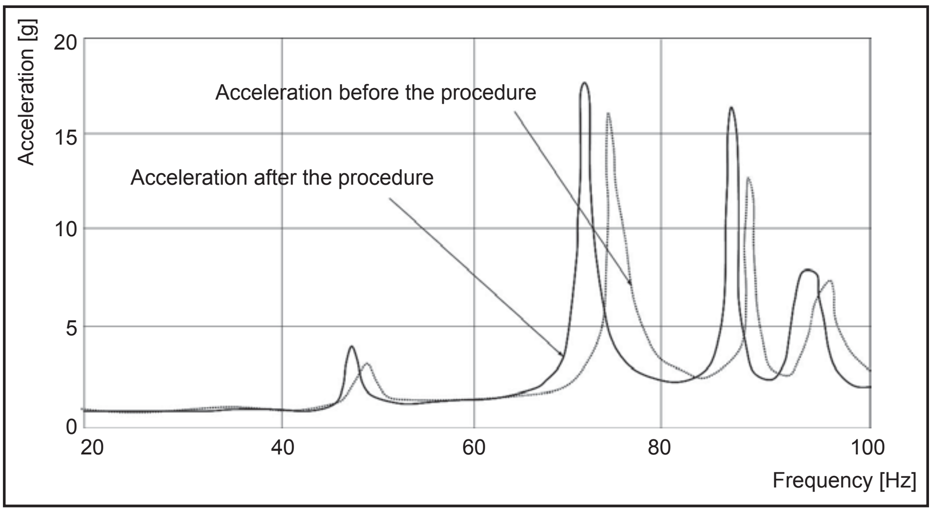


Fig. 1 Changes of acceleration and power of a vibrator in relation to frequency

presented in Figure 1 was performed in two stages, i.e. the first during calibration (searching for resonant frequencies) and the second after the procedure mentioned above. As can be seen, the above named courses vary. After the procedure, the resonance peaks grow and move towards lower frequencies. The authors of the publication unequivocally confirm an improvement in the dimensional stability of a structure subjected to a vibratory procedure. A certain change of material properties of the structure is not directly associated with the reduction of technological stresses. The authors' multi-annual experience confirms this phenomenon. It is maintained that a reduction may take place if amplitudes of variable stresses caused by vibration of the structure are so high that plastic strains lead to their reduction as a result of summing up with technological stresses, which is also confirmed in other publications [1, 2, 18, 19]. However, this observation is not always interpreted in such a manner, particularly by some producers of equipment. Technical materials provided by companies manufacturing vibratory materials state that dimensional stability results from a significant reduction of welding or casting stresses. Also the name of "vibratory stress relief" seems to imply the foregoing.

## Individual Tests and Experiments

The multi-annual tests and experiments performed by the first author of this article in the use of vibratory techniques in technological purposes confirmed the effectiveness of these techniques but only in terms of dimensional stability. Very optimistic information concerning the reduction of welding or casting technological stresses after vibratory procedures inspired several research programmes leading to the development of a number of technological systems and guidelines concerning the proper use of vibratory technologies. The confirmation of the reduction of welding stresses required performing extensometric measurements of variable stresses during vibratory processes [13, 14]. Measurements on elements of actual machine structures were performed in order to verify the usability of vibratory processes in order to eliminate stress relief annealing. The test results revealed that when an eccentric vibrator (having a maximum dynamic force of 15 kN at 6000 rev./min) was used, amplitudes of variable stresses were restricted within a range of several to 50 MPa. Even the phenomenon of resonance, causing a certain increase in a mechanical response, did not significantly increase amplitudes of stresses. However, slight post-vibration strains were detected [15, 16, 17].

In order to investigate the effect of variable stresses on the size of welding stresses, strains (if any) and dimensional stability, it was necessary to perform tests, the results of which are presented in publication [18]. The test results revealed that the noticeable reduction of welding stresses took place only when stresses arising from dynamic forces exceeded the half of the yield point of the structure material.

The cases presented in the reference publications revealed that dynamic forces of the vibrators used were unable to generate sufficient stresses providing conditions for the reduction of stresses in structures of presented dimensions. The publications did not mention the necessary consistency of the directions of welding stresses and of dynamic excitation-triggered stresses. None of the articles referred to above mentions this issue. The lack of the reduction of welding stresses does not justify the conclusion that vibratory processes do not have any effect on the states of structures subjected to vibratory processes. It was noticed that vibratory processes were followed by dimensional stability of effectiveness similar to that of stability obtained after natural stabilising [17, 18].

## Summary of Opinions

Summarising the opinions presented above, it can be stated that there are two theories defining the effectiveness of vibratory processes used in machine building technology. The first theory, represented by some manufacturers of vibratory systems, refers to this process as vibratory stress relief and claims that the use of vibratory processes leads to a significant reduction of welding or casting stresses and, as a result, can replace stress relief annealing. The reduction of technological stresses is explained by plastic strains present during vibration, particularly in the conditions of resonance. However, there seems to be a lack of consistency, as some companies, when presenting their technical information, prefer vibratory processes to be performed in sub-resonant conditions [21]. How to explain the possible generation of such high variable stresses triggering the process of stress reduction in cases when electromechanical vibrators of offered technological systems usually generate a dynamic force of no more than 20 kN? Therefore, it can be stated that the opinion presenting the application of vibratory processes aimed to reduce technological stresses is not entirely reliable. The same information materials present examples of vibratory technique applications exclusively concerning the obtainment of the dimensional stability of a structure, which is important as regards elements subjected to machining. The reference publications did not contain an example of a pressure device in which, following related regulations, it was necessary to reduce welding stresses in order to improve operational properties, e.g. brittle crack resistance. The tests described in [13-19] explicitly revealed that vibratory processes contributed to the obtainment of dimensional stability in structures, and not to the reduction of welding stresses. None of the cited publications presented complex tests combining the dependence of the size of welding stresses on the size of stresses triggered by dynamic excitations with reliable measurements of welding stresses in various states of an object.

The second theory, also shared by the author of this article states that vibratory processes performed using systems available on the market leads to the obtainment of dimensional stability not necessarily connected with the visible reduction of stresses. In the authors' opinion, such a discrepancy of opinions does not serve the practical popularisation of vibratory processes referred to as vibratory stress relief, which in fact should be called vibratory stabilisation. The vibratory method used for increasing dimensional stability finds increasingly many applications in the making of welded machinery structures. The most advantageous effect in the form of dimensional stability is obtained with vibration of resonant frequency. Vibration-induced stresses accelerate processes of microrelaxation and phase transformations at ambient temperature and, as a result, delayed strains. In addition, some material properties, e.g. a damping decrement, can change as well. These phenomena can be manifested by the change of the dependence of the acceleration amplitude in the function of frequency. Vibration results in such a "provocation" of strains that after mechanical treatment the construction does not deform in an unallowed manner. During vibratory stabilisation, the reduction of internal welding stresses is slight, which should be remembered when selecting structures for vibratory stabilisation.

Vibratory stabilisation should be used when making structures subjected to post-weld machining and cannot be used with structures requiring the reduction of internal stresses (e.g. pressure vessels, pipeline or structures where the reduction of stresses conditions an increase in fatigue strength or corrosion resistance). Vibratory processes enable the obtainment of dimensional stability similar to that obtained from resonant stabilising. The best results in terms of dimensional stability can be obtained for such machine structures as wheelcases, machine bases, bases of drive units, housings of electric motors and generators, elements of metallurgical machinery (rolling manipulators, frames and supporting beams of machining equipment, rims of high and medium power toothed wheels etc.) subjected to precise machining during technological processes.

## Vibratory Stabilisation at Instytut Spawalnictwa

Instytut Spawalnictwa has been using the process vibratory stabilisation for several decades. Research and tests conducted in the above named period have led not only to the development of a related technology and the improvement of its effectiveness but also to the development of a number of technological systems which have been successively implemented in the industrial practice.

It is worth studying the history of the development and use of vibratory stabilisation systems. All the systems produced both in Poland and overseas have common design features. The primary element is an inductor in the form of an eccentric vibrator or another, e.g. using a magnetostrictive effect. All vibrators are powered and controlled from a control panel. The systems are equipped with systems measuring amplitudes of accelerations.

The first version of an SW01 vibratory stabiliser developed at Instytut Spawalnictwa in the mid-1980s, based on a DC motor drive with a thyristor control system, was operated manually. The device was provided with an amplitude sensor (Fig. 2).

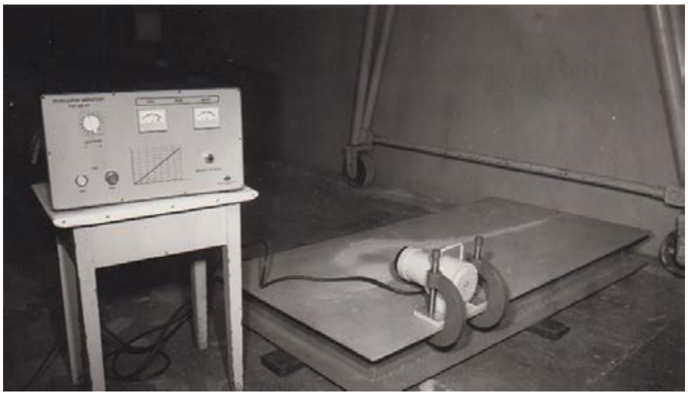

Fig. 2. Station with the SW01 stabiliser

The vibrator was mounted directly on a structure using bolt stays. A structure to be stabilised had to be properly positioned on the base as the greatest effectiveness requires good insulation of vibration from the base, e.g. by using cushions on which the element is placed. The SW01 stabiliser was not provided with a function of automatic recording of a process and saving its results in a memory. Properly performed vibratory stabilisation processes required that the vibrator achieve the resonant frequency of the structure. To this end, it was necessary to use a measurement of vibrator motor current. The eccentric vibrator enabled the operation within the frequency range of 0 to 100 Hz at a maximum dynamic force of 14 kN. The deflection of the vibrator eccentric could be adjusted, which was important if elements to be stabilised were characterised by high amplitudes of strains, which in turn could overload the motor and entailed the necessity of motor operation close to sub-resonant frequencies.

Another vibratory stabiliser manufactured at Instytut Spawalnictwa, i.e. SW02A, was advanced and based on an asynchronous drive from the SW02 type motovibrator [22, 23]. When an AC asynchronous drive was used, due to different motor load characteristics, it was not possible to use the measurement of load current for recording the process of stabilisation, particularly the amplitude of strains on stabilised elements. For this purpose, it was necessary to use a sensor of accelerations. The control system enabled the automatic tuning of resonant frequencies and operation in automatic and manual modes. In addition, it was possible to store data in memory, save them as files on a floppy disc and print out courses of processes using an external printer. Figure 3 presents a station with the SW02A stabiliser.

A system designated as SW03A (Fig. 4) was another modification, featuring a modern, typical and ergonomic housing, which significantly reduced production costs. The system was equipped with a built-in printer and a heavy-duty sensor of amplitude of accelerations, which in turn eliminated incidental failures compromising reliability. A floppy disc recording system was eliminated due to its little usefulness. Modified software improved the system functionality. The vibration inductor applied in the SW03A system was the proven SW02 motovibrator.

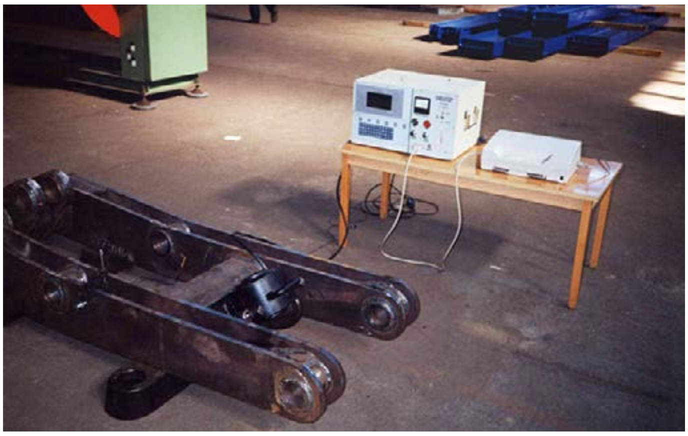

Fig. 3. Station with the SW02A stabiliser

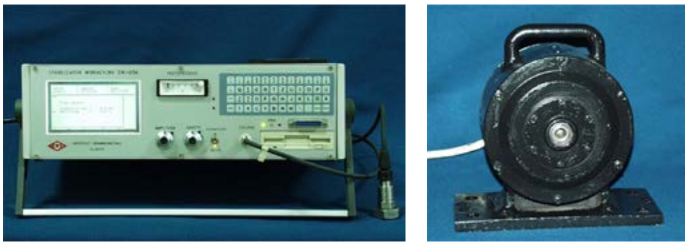

Fig. 4. SW03A stabiliser


Fig. 5. Control panel of the SW04P stabiliser

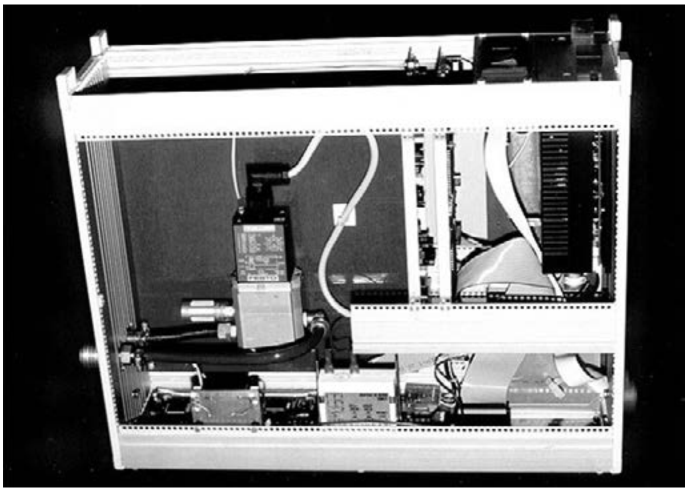

Fig. 6. Interior of the SW04P stabiliser control panel with the proportional valve

Instytut Spawalnictwa also developed an SW04P system, based on a stabiliser provided with a pneumatic drive (Fig. 5) [24, 25]. This development resulted from the necessity of increasing frequency and the possibility of using stabilisation in the production of smaller elements. The system was based on two types of pneumatic vibrators. The first vibrator was an NCT–108 turbine type having a maximum rotation rate of 12 000 min$^{-1}$ (200 Hz) at a pressure of 6 bar, a maximum dynamic force of 8537 N (at a pressure of 6 bar and efficiency of 1226 l/min) and a noise level of 84 dB. The second vibrator was an NCR–3 roller type, having a maximum rotation rate of 40 500 min$^{-1}$ (675 Hz) at a pressure of 6 bar, a maximum dynamic force of 2789 N (at a pressure of 6 bar and efficiency of 190 l/min) and a noise level of 88 dB. The second stabiliser was characterised by different functional features. Particularly when tuning resonant frequency another energy carrier (air characterised by high compressibility) precluded the use of the automatic type.

The vibrators were supplied via an MPPE-3-¼-6-010B proportional valve manufactured by Festo, enabling the precise air flow control within the range of pressure of 0 to 6 bar at a flow rate restricted within a range of 0 to 1500 l/min and a pressure of 8 bar (Fig. 6). The control system was built-in and the connection with the vibrator was via quick-release couplings located on the housing of the prototype.

The SW04P stabiliser supplemented a complex solution consisting in the elimination of stress relief annealing from the greatest possible range of welded and cast structures, including small-sized structures (having a weight of 20 kg and more). The latest vibratory stabilisation system (developed in the last two years) is designated as SW05A. It is an entirely new design, yet largely based on previous successful solutions. The most important feature is the extended possibility of vibration excitation based on the use of two motovibrators. One of them is the previously used SW02 vibrator having a maximum frequency of 100 Hz. The second vibrator, designated as SW03, has a maximum frequency of 200 Hz. Both motovibrators are presented in Figure 7.

The technological set for vibratory stabilisation consists of a control system located in a separate housing, a PC (laptop) for controlling the operation, a motovibrator and an acceleration sensor. The communication between the control system and the laptop is via USB. The control system processes (using a measurement card) commands from the control system (installed in the PC) and transforms them into electric quantities necessary for a process. The control set (module and PC) is presented in Figure 8.

Figure 9 presents the PC screen. The entire communication is via the PC. The screen is divided into sections dedicated to entering data, monitoring and visualising the vibratory stabilisation of a structure. Identifying data are entered using a keyboard and contain the user name, address etc. Data identifying the structure and process include the order number, the structure name, the symbol of the structure or the number of the drawing, the serial number, the grade of the material etc. The process identification section is used for entering data related to the motovibrator used (100 or 200 Hz), the position of the vibrator and data identifying the operator. The system enables entering other data necessary for ensuring the proper performance of processes. In cases of multi-procedure processes (several positions and/or locations of the motovibrator on the same structure), it is possible to use a "Vibrator position" window when identifying individual component procedures. On the basis of a computer system clock, the software application automatically saves the date and commencement time of a vibratory stabilisation process. In addition, this information is also displayed in the section of date and time.

System SW05A enables the manual and automatic performance of procedures. All parameters are saved and controlled appropriately. The system is not provided with a printer; the procedure parameters are

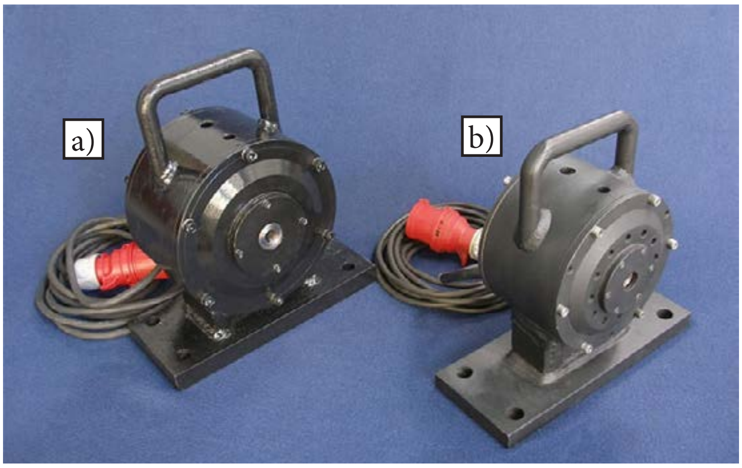


Fig. 7. Motovibrators: a) SW02 (100 Hz), b) SW03 (200 Hz)

Fig. 8. SW05A control set

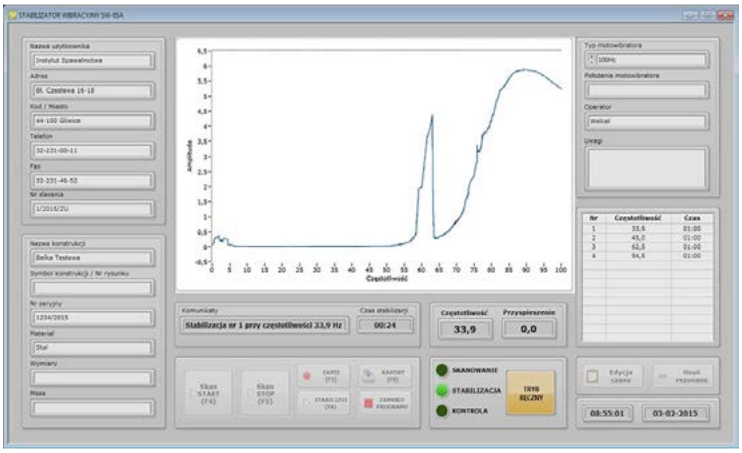

Fig. 8. SW05A control set

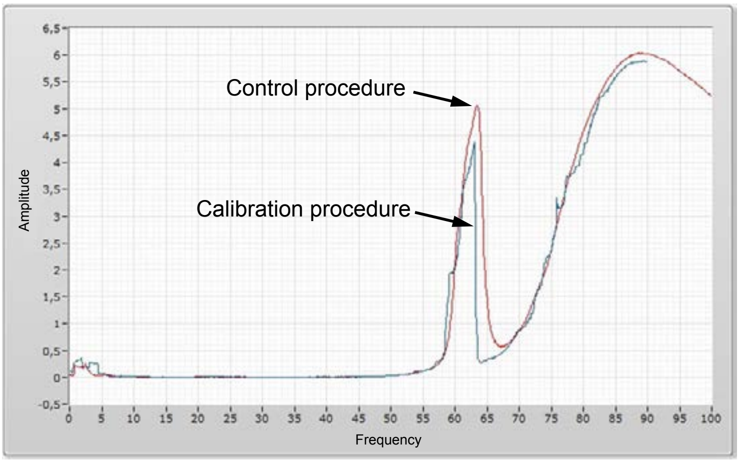


Fig. 10. Changes of the amplitude of accelerations

saved in the form of a report in the mass storage or, via a USB port, in a pen drive. The system can transfer a report to any IP address via Wi-Fi or, if possible, via a wired network. If a printer is provided with an Internet socket, it can directly print a procedure report. As regards technological procedures, it is possible to record a calibration procedure, recording the amplitude of accelerations in the function of frequency and a control procedure of the same dependence. Figure 10 presents "overlapping" courses of the amplitude of accelerations in the function of frequency for the calibration and control procedures. The new system is based on the state-of-the-art systems of industrial electronics, where it is possible to use advanced programming systems supported by standard PCs. The performed tests confirmed the reliability of the control system and the required service life of both motovibrators. Presently, the system SW05A constitutes a new implementation offer of Instytut Spawalnictwa.

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