Modelling and Designing of Ultrasonic Welding Systems

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This article presents the main stages and challenges in modelling and designing of modern ultrasonic welding and cutting systems. First, the key components of such a system, such as an ultrasonic stack (consisting of a high power ultrasonic transducer and a sonotrode) and a digitally controlled ultrasonic power supply with precise control of the output power, have been considered. Next, a concept of measurement system for verification and validation of mathematical models of ultrasonic stacks and its components has been presented. Finally, a method of ultrasonic stack e-diagnosis based on ultrasonic transducer electrical impedance measurement during welding and cutting process has been described.

Keywords: ultrasonic welding and cutting system, ultrasonic stack modelling and designing, digitally controlled ultrasonic power supply, ultrasonic stack e-diagnosis.

1. Introduction

Ultrasonic welding and cutting technologies (ENSMINGER, BOND, 2012; KLUK, 2009a) use mechanical waves in the frequency range from over a dozen kHz to about 70 kHz to join plastic and metal parts. The key elements of an ultrasonic welding and cutting system have been shown in Fig. 1.
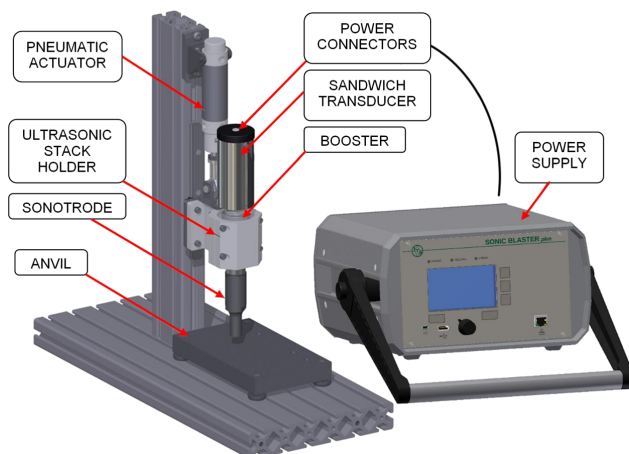

Fig. 1. Key elements of an ultrasonic welding and/or cutting system.

In reality, the ultrasonic welding and cutting system is often equipped with additional elements such as transporters, servomotors, actuators, and so on. As

an example, the ultrasonic welding system for bonding PVC corner angles with fiberglass mesh (NAFALSKI *et al.*, 2010) – developed by Tele and Radio Research Institute (ITR) – has been presented in Fig. 2. The sys-
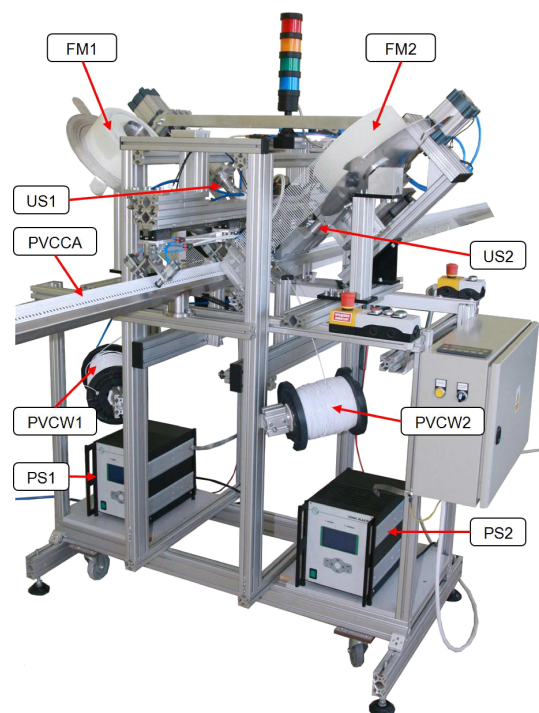

Fig. 2. Ultrasonic welding system for bonding PVC corner angles with fiberglass mesh.

tem is equipped with two power supplies (PS1, PS2) feeding two ultrasonic stacks (US1, US2) in order to bond fiberglass mesh (FM1, FM2) at both edges of the PVC corner angle (PVCCA) simultaneously, using PVC wires (PVCW1, PVCW2).

During the ultrasonic welding or cutting process the welded or cut elements are placed between the steel anvil and sonotrode and are pressed together with the pneumatic actuator at the pressure of up to 1 MPa. Then the ultrasonic welding or cutting cycle is started, i.e., the ultrasonic power supply starts to generate an electric signal feeding the ultrasonic stack consisting of the high power ultrasonic electro-mechanic transducer, the booster, and the sonotrode. The mechanical vibrations generated by the transducer are amplified by the booster and sonotrode assembly. As the result, the mechanical vibrations amplitude at the sonotrode working surface can be as high as tens of micrometers. The mechanical waves propagate through the welded elements causing the melting and mixing of particles of the welded materials forming a firm joint. The ultrasonic welding and cutting process is very fast and energy efficient, because the ultrasonic energy is supplied exactly where it is needed and in short bursts. Moreover, there is no need to use additional substances such as glues, solvents, rivets, and the like. The resulting joint is uniform, clean, tight, and of high strength – often higher than the strength of welded elements. Thanks to these advantages, the ultrasonic welding and cutting technology has been widely used recently, and it gradually replaces all other traditional bonding technologies. However, to develop a good – i.e., efficient, reliable, and producing high quality joints – ultrasonic welding and cutting system, a couple of key development problems must be taken into account and solved. In fact, the contemporary ultrasonic welding and cutting system is a product of mechatronics (KSIĄŻEK, KLUK, 2010), where mechanics, electronics, informatics, and control must be combined in order to obtain usable and high quality products. In this paper, the most vital elements of an ultrasonic welding and cutting system – i.e., the ultrasonic stack and power supply – have been under consideration.

2. Ultrasonic stack modeling and designing

2.1. State-of-the-art

Modern ultrasonic welding systems are used in mass production in a continuous working mode, hence any malfunctionings of the system are usually very costly to the manufacturer. One of the great challenges in the ultrasonics welding and cutting domain is to increase the reliability and lifetime of the ultrasonic stack. In Fig. 3 the main components of the ultrasonic stack have been shown.
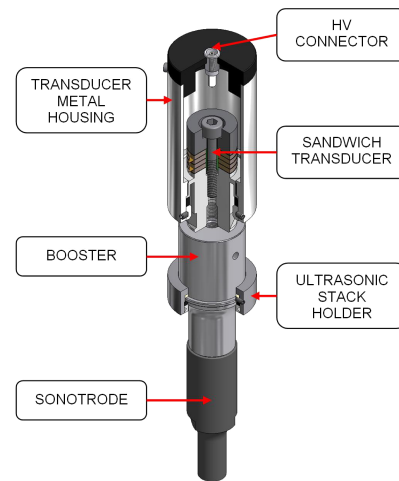

Fig. 3. Main components of the ultrasonic stack.

During welding or cutting process the ultrasonic stack components are exposed to high electrical and mechanical stress. The high power ultrasonic sandwich transducer is excited into mechanical vibrations using electrical sine wave with RMS value up to 3.2 kV. The resulting amplitude of mechanical vibrations – measured at the head of the sonotrode – can be as high as several dozen of micrometers. The ultrasonic stack is pressed to the welded or cut material by the pneumatic actuator with the pressure up to 1 MPa. Resulting high-frequency vibration stress leads to systematical degradation of all the components of the ultrasonic stack. As a consequence, the ultrasonic stack lifetime (MTBF) can be as short as a few months and no longer than a few years – depending on the used sonotrode material (duraluminium, steel, or titanium) and the ultrasonic stack load. The very high cost of materials (especially piezoceramic rings and titanium) and ultrasonic stack manufacturing process (e.g., high precision tooling for titanium sonotrodes) are the main reasons for increasing the ultrasonic stack lifetime. In order to obtain high quality and long lifetime ultrasonic stack, its elements should be appropriately designed using adequate mathematical models.

2.2. High power ultrasonic transducer modeling

The high power ultrasonic transducer is usually built as a stack of piezoceramic rings – forming a so called sandwich transducer. As an example, a 4-ring, 20 kHz, 4 kW sandwich transducer, developed and manufactured by ITR, has been shown in Fig. 4. At the first stage of modelling the geometrical model is simplified in order to obtain axial symmetry. The detailed and simplified geometrical models of that transducer have been presented in Fig. 5 and 6, respectively.

Next, having axial symmetry of all the elements, we can use one of the commonly known analytical models (PROKIC, 2004; RADMANOVIĆ, MANČIĆ, 2004) to
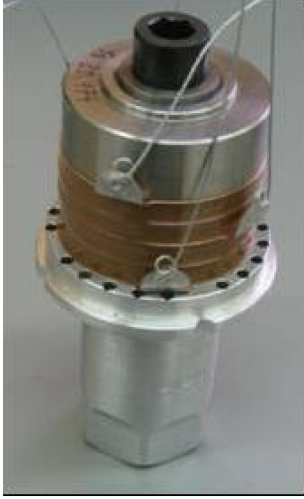
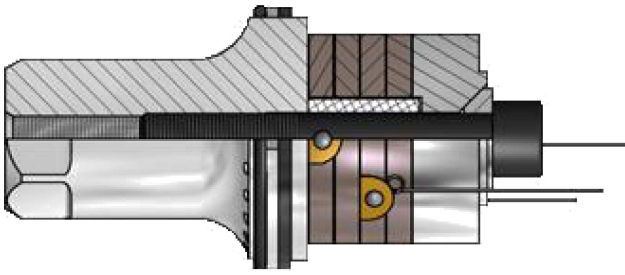Fig. 4. 4-ring, 20 kHz, 4 kW sandwich transducer manufactured by ITR.

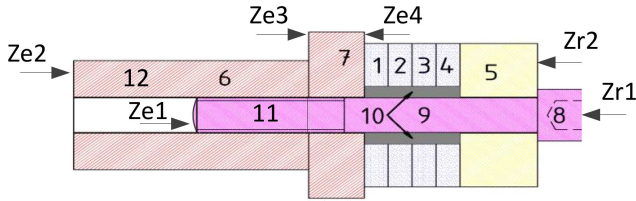Fig. 5. Detailed geometrical model of sandwich transducer.

Fig. 6. Simplified geometrical model of sandwich transducer.

model axial vibrations of each of the elements separately. For example, each of the piezoceramic rings (elements 1–4 in Fig. 6) can be modelled as a three-port network shown in Fig. 7.
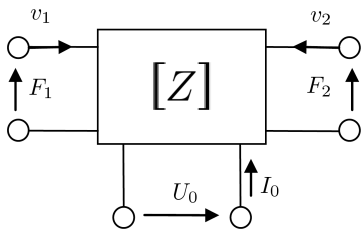

Fig. 7. Three-port network model of the piezoceramic ring.

Solving the general wave equation for the piezoelectric transducer electromechanical vibrations under electrical harmonic excitation leads to the following mathematical model for axial vibrations of a piezoceramic ring:

$$F_1 = \frac{Z_c}{i}\left[\frac{1}{\tan(2hk_3)}v_1 + \frac{1}{\sin(2hk_3)}v_2\right] + \frac{e_{33}}{i\omega\varepsilon_{33}^S}I_0, \quad (1)$$

$$F_2 = \frac{Z_c}{i}\left[\frac{1}{\sin(2hk_3)}v_1 + \frac{1}{\tan(2hk_3)}v_2\right] + \frac{e_{33}}{i\omega\varepsilon_{33}^S}I_0, \quad (2)$$

$$U_0 = \frac{1}{i\omega}\left\{\frac{e_{33}}{\varepsilon_{33}^S}v_1 + \frac{e_{33}}{\varepsilon_{33}^S}v_2 + \frac{1}{C_0^S}I_0\right\}, \quad (3)$$

$$Z_c = \rho v_3 A, \quad (4)$$

where F_1, F_2 are the external mechanical force loads, v_1, v_2 are the external particle velocity loads, I_0 is the electrical current, U_0 is the electrical voltage, C_0^S is the static capacitance at constant strain, v_3 is the phase velocity in axial direction, k_3 is the wave number in axial direction, ρ is the material density of the piezoelectric transducer, A is the area of the acoustic boundary surface in axial direction, 2 h is the piezoceramic ring thickness, Z_c is the characteristic acoustic impedance of the piezoceramic transducer, ω is the angular frequency, e_{33} is the piezoelectric constant, ε_{33}^S is the dielectric permittivity at constant strain.

The acoustically loaded model of the piezoceramic ring has been shown in Fig. 8. The impedances Z_1 and Z_2 are acoustic impedances of the external acoustic medium attached to both of the vibrating surfaces of the transducer.
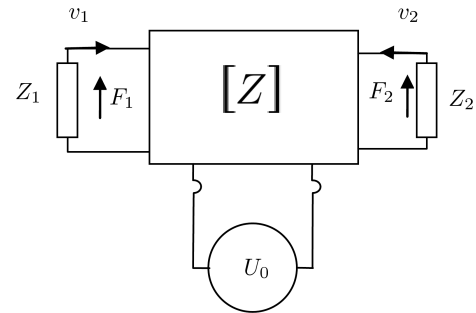

Fig. 8. Acoustically loaded model of a piezoceramic ring.

For such a model the electrical impedance can be evaluated using the following expression:

$$Z = \frac{U_0}{I_0} = \frac{1}{i\omega C_0^S}$$
$$\cdot\left\{1 - \frac{k_t^2}{hk_3}\frac{\frac{1}{2i}(Z_1 + Z_2) + \rho v_3\tan(hk_3)}{\frac{Z_1 Z_2}{\rho v_3} - i\frac{(Z_1+Z_2)}{\tan(2hk_3)} + \rho v_3}\right\}, \quad (5)$$

where k_t is the electromechanical coupling factor for thickness vibration mode. An exemplary electrical impedance characteristic of the SonoxP8 piezoceramic ring (dimensions $50\times20\times6$) simulated for catalogue

parameters according to the expression (5) has been shown in Fig. 9. The discrepancy between simulated and measured impedance is due to:

- Relatively large scattering (about 20%) of piezoceramic ring parameters between production lots;
- The fact that the model (6) does not take into account other modes of vibrations, especially radial modes which affect the effective phase velocity of the modelled vibration axial mode;
- The fact that the model (6) has been derived for the axial vibration of an infinitely thin piezoceramic disc for which lateral interactions can be neglected.
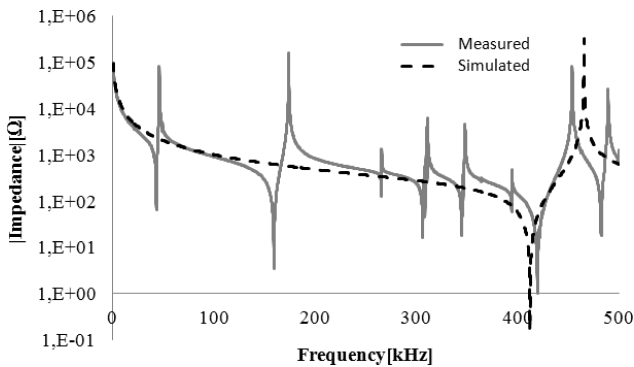

Fig. 9. Measured and simulated absolute impedance characteristic of the examined SonoxP8 piezoceramic ring.

By combining n-port network models of all the sandwich transducer elements we obtain a multi-port network model of the sandwich transducer which has been shown in Fig. 10. The insulating plastic sleeve, shown in the Fig. 6 as the element number 10, does not participate in the vibration, so it is not included in the model. While designing the multi-port model one should take into account the following rules, resulting from the boundary conditions:

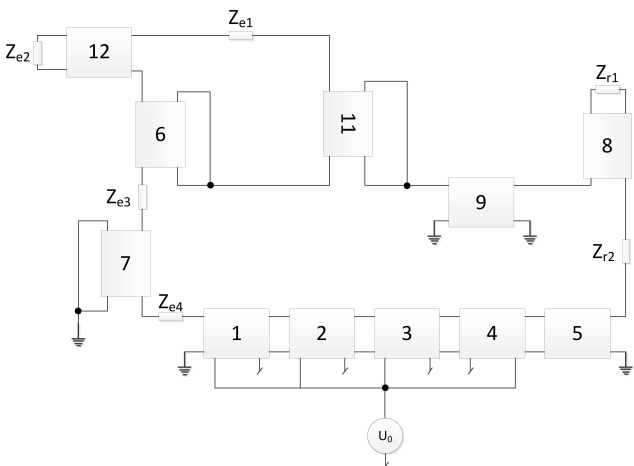- The vibration amplitude on every contact surface must be continuous (equal) in the transducer axis

direction, as well as the particle velocity and the force;

- Continuous force distribution at the contact surface between two elements (elements 1–5) implies the cascade connection between them; otherwise, if more than two elements are connected, the serial connection should be used (elements 5, 8, 9);
- The piezoceramic rings (elements 1–4) are connected in parallel electrically.

The multi-port network model is extremely useful in the development process of sandwich transducers. For example, this model can be used for electric impedance estimation, modal frequencies estimation, and electromechanical coupling coefficient optimization. It can also be used for studying the transducer behavior under the influence of acoustic load.

2.3. Sonotrode modelling

For simple sonotrode shapes with axial symmetry, e.g., cylindrical, step, exponential, or conical, the commonly known analytical models can be used (Radmanović, Mančić, 2004). The models are based on the assumption of plane wave propagation and are not adequate for complex sonotrode shapes. Moreover, the sonotrode shape is optimized in order to obtain optimal mechanical displacement and stress distribution (optimal radiation pattern) ensuring the most efficient transfer of vibration energy to the load (welded material). So, the sonotrode shape is closely related to a specific ultrasonic welding and cutting technology. For example, in rotary welding technology the shape of sonotrode is optimized in such a way that the conversion between axial and radial modes is most efficient (Kogut *et al.*, 2013). In that case, it is necessary to use the numerical model – i.e., the FEM model – in order to obtain adequate accuracy of modelling. As an example, the geometrical model of the rotary welding sonotrode developed by ITR along with its FEM model has been shown in the Fig. 11. The shape and dimensions of the sonotrode have been iteratively op-

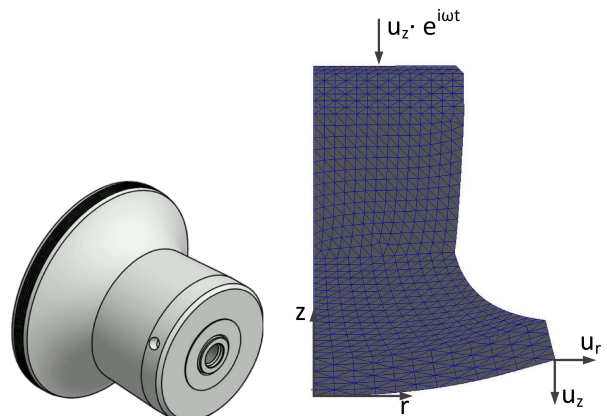Fig. 10. Multi-port network model of the sandwich transducer.

Fig. 11. Rotary welding sonotrode and its FEM model.

timized using FEM model in order to obtain maximum efficiency in converting axial vibrations from the ultrasonic transducer into the axial and radial vibration components (u_r and u_z) at the sonotrode working edge.

3. Ultrasonic power supply design challenges

In modern ultrasonic welding and cutting systems the power supply is generally an AC-AC power converter (MOHAN *et al.*, 2003) with digitally controlled frequency and amplitude of the electric output signal. The output power is in the range of hundreds of watts to a few kilowatts, and the frequency range is of 20 kHz to 70 kHz. In order to obtain high power efficiency under these conditions the only solution is to use a resonant converter (CHUDORLIŃSKI, KARDYŚ, 2010), (KARDYŚ *et al.*, 2013). One of the main problems are changes that occur in the material during welding or cutting process, e.g., material melting that result in rapid changes in the ultrasonic stack impedance. Without a precise follow-up control of frequency and amplitude of the electric signal feeding the ultrasonic stack the power supply output power will fluctuate strongly during welding and cutting process resulting in bad quality of the process. Most power supplies try to follow one of the resonance frequencies, like in (KLUK, WLAZŁO, 2009), but the optimal operating point lies somewhere between the anti-resonance and resonance frequencies, as has been presented in Fig. 12.
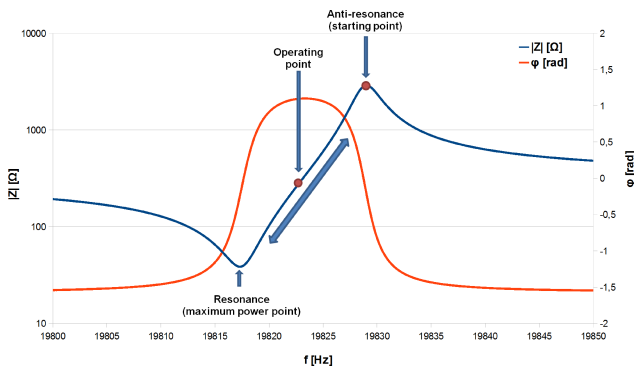

Fig. 12. Optimal operating point lies somewhere between anti-resonance and resonance frequencies.

In order to develop a method of finding and following the optimal operating point many investigations have been conducted by ITR. As a result, an innovative method of ultrasonic stack active power stabilization has been developed (KLUK, 2009b; BRYLSKI, 2010b). The active power is estimated in real-time according to the following equations:

$$P = \frac{1}{2} |U_1| |I_1| \cos(\varphi), \qquad (6)$$

$$\varphi = \arg(U_1) - \arg(I_1). \qquad (7)$$

The power is stabilized in real-time by controlling the inverter frequency with a step equal to 0.1 Hz. The method has been implemented in a power supply using a dual core DSP processor, a Direct Digital Synthesis (DDS), and a Complex Programmable Logic Device (CPLD) to control the resonance voltage inverter (MILEWSKI *et al.*, 2011). Basing on that method a new strategy for defining the ultrasonic welding and cutting process as the active power vs. time function (BRYLSKI, 2010a) was developed. The method allows to obtain optimal and reproducible welding and cutting results while minimizing energy consumption.

4. Ultrasonic stack verification and validation

The high quality welding and cutting demand predetermined frequency characteristics of the transducer impedance. Also important are: high energy efficiency, high coupling coefficient, low dielectric loss, and the optimal radiation pattern. In order to manufacture high quality and long-life transducers the piezoelectric rings must be selected, and the sandwich transducers as well as complete ultrasonic stacks verified and validated on the basis of their measured parameters. For this purpose the measurement system for parameter estimation and diagnostic of ultrasonic transducers has been developed by ITR. The block diagram of the system has been shown in Fig. 13 (KLUK *et al.*, 2013).
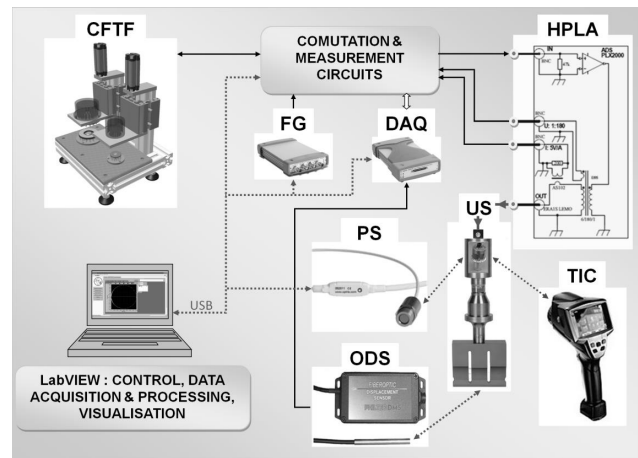

Fig. 13. Block diagram of the measurement system for ultrasonic stack verification and validation.

The system takes advantage of the virtual instrument technique in the NI LabVIEW environment. It uses an Agilent U2761A Function Generator (FG), a U2531A Data Acquisition Unit (DAQ), and the modified 1200 VA acoustic high power linear amplifier (HPLA) for ultrasonic stack (US) electrical impedance measurement, according to the methods described in (KOGUT *et al.*, 2013) and (KARDYŚ *et al.*, 2013). The controlled force test fixture (CFTF) has been designed

for piezoceramic rings measurement and selection. Basing on the impedance frequency characteristic, the RLC equivalent circuit parameters estimation is conducted (MILEWSKI *et al.*, 2011). Additionally, selected piezoceramic material parameters can be estimated. Using a sophisticated graphical user interface of the measurement system the impedance module and phase vs. frequency, and impedance circle can be displayed with resolution up to 0.1 Hz in the frequency range of 10 kHz to 100 kHz. The vibration amplitude can be measured, using the PHILTEC RC25-H3 fiber optic displacement sensor (ODS), in the range of 1 μm to 100 μm, with the resolution better than 1 μm, and visualized in the time and frequency domains (KLUK *et al.*, 2013). The sandwich transducer temperature map can be obtained using the thermal imaging camera (TIC). For a sandwich transducer closed in a metal housing, the pyrometer sensor (PS) fixed in the hole in the housing must be used instead of the camera.

The measurement system has been successfully used for verification and validation of mathematical models of ultrasonic transducers (MILEWSKI *et al.*, 2012). Using that system we can shape and verify the frequency response of the manufactured transducers and ultrasonic stacks. Having the reference impedance characteristic we can store it in an ultrasonic generator and compare it with the actual one for the purpose of ultrasonic stack e-diagnostic and wear monitoring.

5. E-diagnosis in ultrasonic welding system

E-diagnostic and wear monitoring of the ultrasonic stack are very essential issues in ultrasonic welding and cutting systems. On the one hand, the cost of materials and manufacturing of the ultrasonic stack is usually very high. On the other hand, the systematic ultrasonic stack degradation can influence the ultrasonic welding and cutting process quality, and in extreme cases the joint quality becomes unacceptable. A malfunction of one of the ultrasonic stack parts leads usually to damage of other parts (even the anvil) of an ultrasonic welding and cutting system. Hence, early detection of any malfunction in an ultrasonic stack is very important in order to avoid the impeding system breakdown, which is usually very costly for the manufacturer. The assessment of the state of the ultrasonics stack can be accomplished on the basis of electrical impedance monitoring during the welding and cutting process. In the process of development and manufacturing of ultrasonic stacks in ITR the ultrasonic stack impedance characteristics are developed and verified adequately to the requirements of a particular ultrasonic technology. The parameters of impedance characteristics such as resonance and anti-resonance frequencies, absolute value of impedance at resonance frequency, and the absence of parasitic resonances are one of the main factors in the quality assessment of the ultrasonic transducers and stacks. The parasitic resonances disqualify the ultrasonic stack to continue the work, because they are local minima in impedance characteristic, and the ultrasonic generator can easily tune to one of them and get stuck in there resulting in bad quality welding or cutting process. Exemplary ultrasonic sandwich transducer impedance characteristics have been shown in Fig. 14. These characteristics have been measured for a good quality 20 kHz ultrasonic transducer. There are no parasitic resonances and the absolute value of impedance at the resonance frequency measured for the unloaded transducer is about over a dozen ohms ($R = 15\,\Omega$ in the series equivalent RLC circuit).
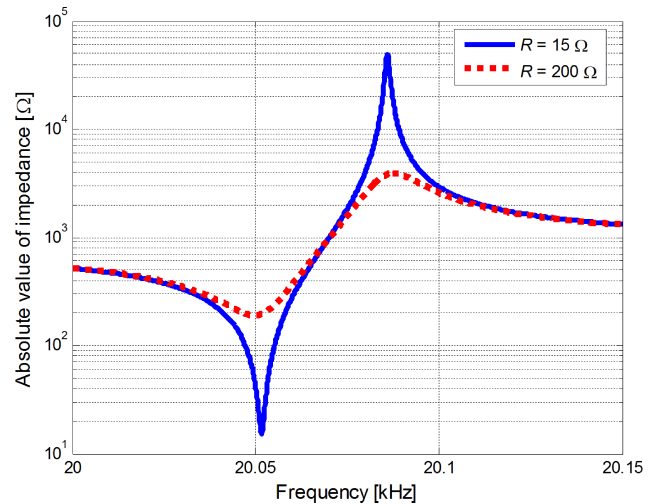

Fig. 14. Ultrasonic transducer impedance characteristics.

The degradation of the ultrasonic stack is reflected in impedance characteristics changes, such as increasing the impedance module in the serial resonance or the appearance of parasitic resonances. An excessive increase in ultrasonic stack temperature also significantly affects the parameters of the electrical impedance characteristics. Hence, the following general diagnosis method can be used to monitor the health of the ultrasonics stack:

- Parameterization of electrical impedance characteristics and identification of parameters carrying vital information about the health of the ultrasonic stack, e.g., the impedance module in the serial resonance, the distance between the resonance and the anti-resonance, and so on;

- Basing on the estimated values of parameters, classification of the ultrasonic stack state (good or bad) using the universal classifier such as artificial neural network.

6. Conclusions

The issues of adequate modelling and designing of high power ultrasonic devices and e-diagnostic of ul-

trasonic stack are very important in manufacturing efficient, reliable, and long-life ultrasonic welding and cutting systems. Thus, further research will be conducted in this area in order to improve existing systems because there is a practical need for it in today's industry.

References

1. Brylski M. (2010a), *Generation of ultrasonic welding cycle as a function of active power in time* [in Polish], Elektronika, **51**, 7, 102–104.

2. Brylski M. (2010b), *Follow-up power adjustment in ultrasonic assembly of ultrasonic welding system* [in Polish], Elektronika, **51**, 7, 105–107.

3. Chudorliński J., Kardyś W. (2010), *Usage of resonant converters in ultrasonic generators* [in Polish], Elektronika, **51**, 7, 99–102.

4. Ensminger D., Bond L.J. (2012), *Ultrasonics – Fundamentals, Technologies, and Applications*, 3rd Ed., CRC Press, Taylor & Francis Group, Boca Raton.

5. Kardyś W., Milewski A., Kluk P., Kogut P. (2013), *Linear high power amplifier for measurements of nonlinear properties of ultrasonic systems* [in Polish], Elektronika, **54**, 4, 20–23.

6. Kluk P. (2009a), *Architecture of series of types of ultrasonic welding systems with digital feedback* [in Polish], Elektronika, **50**, 7, 74–79.

7. Kluk P. (2009b), *Algorithm of active power stabilization in high power ultrasonic assembly of ultrasonic welding system with digital feedback* [in Polish], Elektronika, **50**, 7, 79–81.

8. Kluk P., Milewski A., Kogut P., Kardyś W., Młynarski B. (2013), *Virtual Instrument for Optical Measurement of Ultrasonic Stack Vibrations* [in Polish], Elektronika, **54**, 4, 23–26.

9. Kluk P., Wlazło P. (2009), *Ultrasonic assembly resonance frequency tracking algorithm in ultrasonic welding system with digital feedback* [in Polish], Elektronika, **50**, 7, 70–74.

10. Kogut P., Milewski A., Kluk P., Kardyś W., Nafalski L. (2013), *Piezoelectric transducer impedance measurement circuit* [in Polish], Elektronika, **54**, 4, 16–19.

11. Książek L., Kluk P. (2010), *Selected applications of ultrasonic technique in mechatronics* [in Polish], Elektronika, **51**, 10, 131–134.

12. Milewski A., Kluk P., Kogut P. (2011), *Automatically controlled ultrasonic power generator* [in Polish], Elektronika, **52**, 9, 198–201.

13. Milewski A., Kluk P., Kogut P., Florkowska-Trąbińska J. (2011), *Parametric validation of the ultrasonic piezoelectric transducers* [in Polish], Elektronika, **52**, 9, 194–198.

14. Milewski A., Kogut P., Kardyś W., Kluk P. (2012), *Experimental validation of the piezoceramic transducers electromechanical models* [in Polish], Elektronika, **53**, 8, 15–18.

15. Mohan N., Undeland T., Robbins W. (2003), *Power Electronics – Converters, Applications, and Design*, John Willey & Sons, USA.

16. Nafalski L., Młynarski B., Krzemiński Ł. (2010), *The application of ultrasonic welding technology to connect to glass fibers grid to the PVC profiles* [in Polish], Elektronika, **51**, 7, 108–111.

17. Prokic M. (2004), *Piezoelectric Transducers Modeling and Characterization*, MPI, Switzerland.

18. Radmanović M.Đ., Mančić D.D. (2004), *Designing and Modeling of the Power Ultrasonic Transducers*, MPI, Switzerland.

19. Kogut P., Milewski A., Kardyś W., Kluk P., Gawryś P. (2013), *New Multimode Sonotrodes Models Designed for Rotary Ultrasonic Welding Systems*, Acta Physica Polonica A, **124**, 3, 474–478.

20. Kardyś W., Milewski A., Kogut P., Kluk P. (2013), *Universal Ultrasonic Generator for Welding*, Acta Physica Polonica A, **124**, 3, 456–458.

21. Kluk P., Milewski A., Kardyś. W, Kogut P., Michalski P. (2013), *Measurement system for parameter estimation and diagnostic of ultrasonic transducers*, Acta Physica Polonica A, **124**, 3, 468–470.