Adaptive Sensor Signal Amplification for Ultrasonic Welding and Wire Bonding

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Abstract

Piezoelectric vibration sensors integrated into the ultrasound system play a vital role for determining joint quality in ultrasonic wire bonding and ultrasonic metal spot welding, for example in Hesse Mechatronics' well-established Process integrated Quality Control (PiQC). This paper describes different strategies for improving sensor signal quality by adaptive amplification.

1. Joint quality sensors in ultrasonic wire bonding and welding

Ultrasonic wire bonding and ultrasonic metal spot welding are common techniques in industrial manufacturing of a wide range of products such as microelectronics, power electronics, and battery packs. Optical inspection as well as destructive and non-destructive mechanical tests like shear, pull, or peel tests are classic methods to evaluate the joint quality of such processes. Online observation of certain parameters over the course of the welding time is nowadays also common in ultrasonic welding and standard in wire bonding. The following quantities are often evaluated:

- Electric current amplitude (if voltage is set) or voltage amplitude (if current is set) or impedance (relation of voltage to current)
- Electric power or (cumulated) energy
- Vertical deformation of the bonding wire respectively welded part
- Vibration frequency (if resonance frequency tracking is used) or phase between voltage and current (if operating at a constant frequency)

Current, voltage, impedance, power, and energy are not independent quantities. Current, voltage, or impedance are commonly observed in wire bonding, while power or energy are more commonly used in ultrasonic welding. If any of the observed quantities are outside certain limits, a joint is regarded as suspicious. Such non-destructive online tests do not consume any time and can thus be applied to 100 % of the joints. As tests have shown that not all bad wire bonds can be identified using current and deformation alone [1, 2], frequency observation is very common in wire bonding nowadays. Still, this does not guarantee identification of all potentially bad joints. Thus, more advanced quality control systems use additional independent quantities to determine joint quality.

One such system, productively used in wire bonders for over a decade and recently also introduced in higher power smart ultrasonic welding systems [3], is Hesse Mechatronics' multidimensional Process integrated Quality Control (PiQC) [1, 2]. It uses a piezoelectric sensor integrated into the ultrasound transducer [2, 4], to evaluate a total of five different physical quantities recorded during the whole process: mechanical vibration of the welding tool, friction in the welding zone, wire deformation, transducer impedance, and operation frequency, i.e. transducer resonance frequency. From their course over the process time, it calculates quality indices for each of these quantities in real-time, based on a previously learned set of reference welds representing a good, stable process.

2. Amplitude and signal processing of mechanical vibration sensor signals

The piezoelectric PiQC sensor produces an electrical signal $u_s(t)$ which provides detailed information about the mechanical vibration of the tip of the bonding/welding tool. A signal amplifier, typically placed close to the high impedance sensor to obtain a high quality signal with low noise, is used to change the amplitude of the signal to match the input range of a connected analog-digital-converter (ADC). Appropriate filters may be placed before the ADC to reduce noise or undesired low-frequency signals.

In piezoelectric transducers operating in or near a resonance, the amplitudes of current $i(t)$ and of the vibration of any defined point are roughly proportional. Thus, while the amplified signal $u_{s,a}(t)$, respectively the raw signal $u_s(t)$, provides valuable additional information about the joining process, its overall amplitude is roughly proportional to the amplitude of the current $i(t)$ through the ultrasound transducer which generates the ultrasonic vibration. This relation is described by

$$\hat{u}_{s,a}(t) \approx \hat{\imath}(t) \cdot S \cdot A, \tag{1}$$

where $S \approx \hat{u}_s(t)/\hat{\imath}(t)$ is the sensitivity of the sensor, with the amplitude of the raw, resp. amplified sensor signals $\hat{u}_s(t)$, $\hat{u}_{s,a}(t)$, the amplitude of the transducer current $\hat{\imath}(t)$, and the amplification factor $A = u_{s,a}(t)/u_s(t)$.

Using this relation, the amplifier is calibrated by setting a standard amplification factor $A = A_0$, exciting the transducer in one or more operating points (defined by current amplitude or voltage amplitude, frequency or phase), and then adjusting A so that $\hat{u}_{s,a}(t)$ is as large as possible but also safely below the input limits of the ADC to avoid clipping (overdriven operation) in the expected operating points. While it cannot affect noise on the raw sensor signal $u_s(t)$, a well-chosen amplification factor A reduces quantization noise by fitting the amplitude $\hat{u}_{s,a}(t)$ of the amplified sensor signal to the input range of the ADC. This results in a good signal-to-noise-ratio (SNR) and a high effective resolution of the digitized signal.

Classically, and before the advent of digital potentiometers, this amplification setting was usually performed a single time during calibration of the ultrasonic system, to a "one fits all" setting which was only rarely adapted later for the individual application. The vibration and thus current amplitude in different applications of the same ultrasonic joining equipment can be very different, though. For example, Hesse Mechatronics thin wire wedge-wedge bondheads can process wires with diameters ranging from 12.5 to 75 µm – a cross-section spread of 36. A fixed amplification setting is thus always a compromise, resulting in a low amplitude of $u_{s,a}(t)$ in low current applications, with the effect of low SNR and poor digitization in the ADC, and bears the risk of clipping in high current applications.

Figure 1 shows real-world examples demonstrating this issue: A wire bonding system is used for three types of joints, where the maximum current amplitude is about 0.05 A, 0.18 A, and 0.54 A, respectively. As described above, the raw sensor signal amplitude $\hat{u}_s(t)$ is roughly identical to the current amplitude $\hat{\imath}(t)$ multiplied with the sensor sensitivity S. Accordingly, the amplitudes of $\hat{u}_s(t)$ (upper diagrams) differ greatly with the three joint types. Using a constant amplification of $A = 11$ (bottom diagrams, dashed lines) allows operation of the sensor in all of these applications, with a maximum of the amplified signal $\hat{u}_{s,a}(t)$ of about 8 V, which is safely below the maximum input level of the ADC of 10 V.

This setting works well for joint type 3, but with joint types 1 and 2, the amplified signal level is low, resulting in low resolution of the digitized signal. For example, if a signal with an amplitude of 8 V (joint type 3) is digitized using a 12-bit-ADC with an input range of 10 V, its effective resolution (neglecting noise) is 11.7 bits. But if the signal amplitude is only 0.74 V (joint type 1), its effective resolution is only 8.2 bits. With an 8-bit ADC, it is 7.7 vs. just 4.2 bits. Also, any noise affecting the analogue amplified signal has a larger effect if the signal amplitude is low.

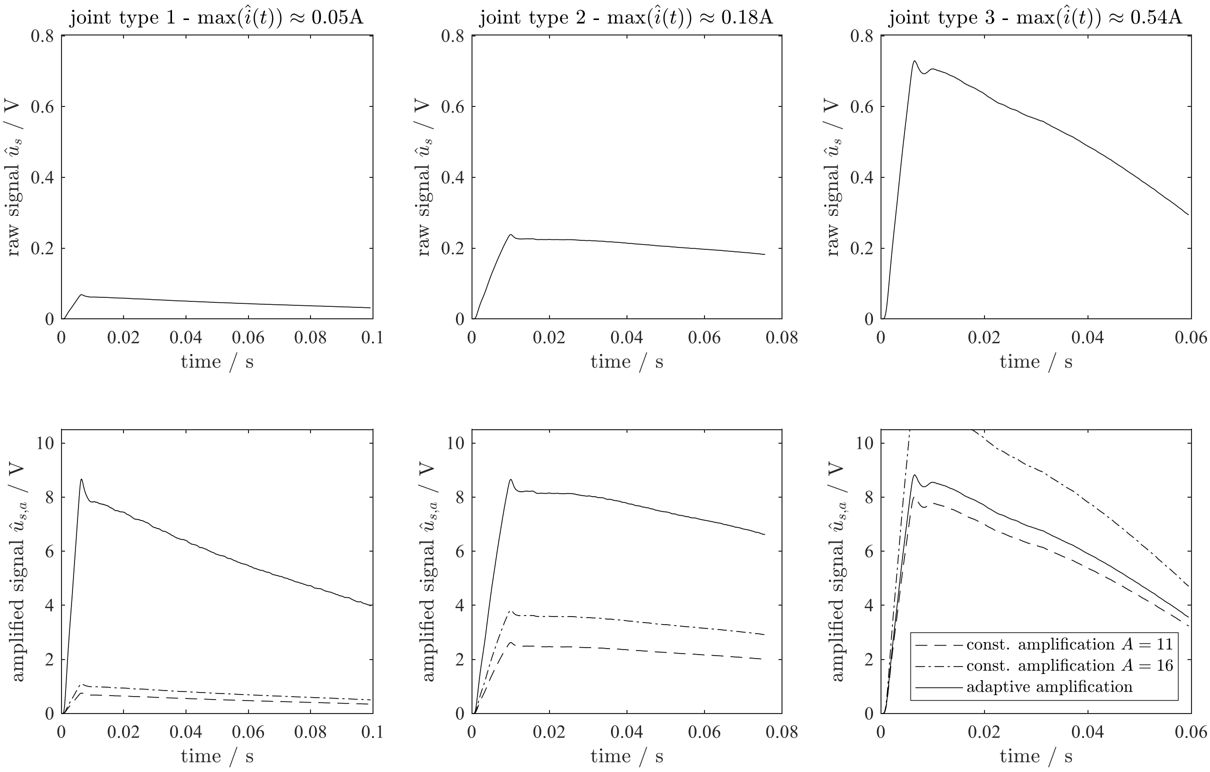

Figure 1: raw and amplified sensor signals for three joints employing different current levels, for two constant amplification settings and using adaptive amplification

Significantly increasing the constant amplification, for example to $A = 16$ (chain lines), increases the signal levels, but results in clipping with joint type 3, because the signal exceeds the maximum of 10 V. Obviously, there is no constant amplification with yields optimum results for all joint types. Using an adaptive amplification (solid lines) would be the solution to this issue, providing low SNR and good digital resolution without clipping for all joint types.

3. Adaptive sensor signal amplification

The following paragraphs describe different strategies to realize such an adaptive amplification. It is important to keep in mind that if there are different types of joints in one product, these strategies must be applied individually to each group of joints. The only exception is the current-based strategy described in the next paragraph, since it does not incorporate any characteristics of the joint.

Obviously, any adaptive sensor amplification requires a design with allows electronic adjustment of the amplification. Such a design can for example be realized using digital potentiometers. The computer controlling the joining process can then set an amplification as close as possible to the optimum for each individual bond.

All the strategies require the (average) sensitivity of the sensor S to be determined in advance. Also, the maximum input voltage $u_{\text{ADC,max}}$, e.g. 10 V as in the examples above, must be known.

3.1. Current-controlled processes

A current-controlled process is a process where the user defines the course of the current amplitude $\hat{\imath}(t)$ during the process. A good ultrasound system (consisting of tool, transducer, power amplifier, and controller) follows this current setting very precisely, so that the computer knows the maximum current amplitude $\hat{\imath}_{\text{max}}$ with sufficient precision for each bond. It can thus set the amplification factor A as

$$\mathrm{A} = s_1 \cdot u_{\text{ADC, max}} / (\hat{\imath}_{max} * S) \quad , \tag{2}$$

where s_1 is a safety factor slightly below 1, e.g. 0.85. This factor prevents imperfections in current control and unforeseen variations in the sensitivity S from causing clipping.

3.2. Voltage-controlled processes without calibration bonds

A voltage-controlled process is a process where the user defines the course of the voltage amplitude during the process. The resulting current amplitude depends on the characteristics of the ultrasound system and the mechanical process. In order to determine a proper amplification factor, the current amplitude is estimated from an additional measurement performed in advance which characterizes the freely vibrating ultrasonic system: Its free admittance $\underline{Y}'$ is measured at different voltage amplitudes $\hat{u}$, resulting in a function $\underline{Y}'(\hat{u})$.

During any joining process, the admittance of the ultrasonic system is lower than in a freely vibrating state. It is typically between 5 % and 50 % of the free admittance, depending on the ultrasound system and the process. Thus, the free admittance at a certain voltage is an upper limit for the admittance to be expected at this voltage during the joining process. Thus, an upper limit $\hat{\imath}'(\mathrm{t})$ for the current amplitude during the process can be calculated as

$$\hat{\imath}'(\mathrm{t}) = \hat{u}(t) \cdot \underline{Y}'(\hat{u}(t)). \tag{3}$$

The maximum of $\hat{\imath}'(\mathrm{t})$ is the maximum possible current amplitude during this process, so the amplification factor can be set as

$$\mathrm{A} = \mathrm{s}_2 \cdot u_{\text{ADC, max}} / (\max(\hat{\imath}'(\mathrm{t})) \cdot \mathrm{S}) \tag{4}$$

where s_2 is again a safety factor. This factor – other than s_1 – may also be chosen above 1, e.g. 1.5, if the ultrasound system is proven to have an adequately low admittance during the welding process. But choosing a value for $s_2 > 1$ requires sufficient knowledge about the process, as it can result in clipping.

Data-based admittance estimation

The procedure described above typically results in relatively low amplitudes of the amplified signal, since the exact admittance during joining is not known and estimates should be conservative to prevent clipping. The following paragraph describes a data-based variant of this procedure which estimates the admittance during joining based on known processes.

The admittance during joining can be roughly modelled as

$$\underline{Y}(t) = \frac{1}{Z_0(\mathrm{t}) + Z_L(t)}, \tag{5}$$

where $Z_0(\mathrm{t})$ is the freely vibrating impedance of the ultrasound system and $Z_\mathrm{L}(\mathrm{t})$ is the impedance added by the mechanical load. Courses of $Z_\mathrm{L}(\mathrm{t})$ can be stored for any process which is set up using a certain type of ultrasound system.

The admittance during a new process can then be estimated based on the data from similar processes, e.g. using the same wire material and diameter and the same substrate surface. Taking the typical minimum load impedance Z_L^* from these processes, admittance $\underline{\mathrm{Y}}^*(\mathrm{t})$ and current amplitude $\hat{\imath}^*(\mathrm{t})$ during the process are then estimated as:

$$\underline{Y}^*(t) = \frac{1}{1/\underline{Y}'(\hat{u}(t)) + Z_L^*} \tag{6}$$

$$\hat{\imath}^*(\mathrm{t}) = \hat{u}(t) \cdot \underline{Y}^*(t) = \frac{\hat{u}(t)}{1/\underline{Y}'(\hat{u}(t)) + Z_L^*} \tag{7}$$

The maximum of $\hat{\imath}^*(\mathrm{t})$ is then used to calculate the amplification factor in eq. (8), which mirrors eq. (4) for a different current estimate. Safety factor s_3 can in this case be chosen below 1:

$$\mathrm{A} = s_3 \cdot u_{\text{ADC, max}} / (\max\,(\hat{\imath}^*(\mathrm{t})) \cdot \mathrm{S}) \tag{8}$$

Practically, Z_L^* can automatically be taken from a database based on ultrasound system and process characteristics. Z_L^* may be stored in the database in conjunction with the freely vibrating impedance of the ultrasound system Z_0 at one or more excitation levels.

3.3. Voltage-controlled processes with calibration bonds

In a stable voltage-controlled ultrasonic joining process, the courses of the current amplitude $\hat{\imath}(\mathrm{t})$ as well as of the raw sensor amplitude $\hat{u}_s(t)$ do not change much from joint to joint. Thus, instead of estimating $\hat{\imath}(\mathrm{t})$, another option is to make one or more “calibration bonds” with a low amplification factor A_0 before regular productive use of the sensor signal. The maximum, mean, or median of the recorded maximum current amplitudes can then be used as $\hat{\imath}_{\text{max}}$ and the amplification factor is calculated using eq. (2), where safety factor s_1 should be chosen lower than with current-controlled processes, e.g. $s_1 = 0.7$.

Alternatively, the maximum, mean, or median of the recorded maximum amplitude of the amplified sensor signal $u_{s,a}(t)$ is determined, called $\hat{u}_{s,a,\max}$ in the following. The amplification factor for production is then calculated as

$$\mathrm{A} = \mathrm{s}_4 \cdot \mathrm{A}_0 \cdot u_{\text{ADC, max}} / \hat{u}_{s,a,\max}\,, \tag{9}$$

where safety factor s_4 can be chosen slightly below 1, e.g. $s_4 = 0.85$. This factor prevents variations in process admittance and other unforeseen variations from causing clipping. Directly working with the sensor signal amplitude is generally preferable over working with the current amplitude since it eliminates the effect of possible variations of the sensitivity S.

In both cases, sensor signals recorded for the “calibration bonds” with amplification factor A_0 can be retroactively scaled to production level by multiplying them with A/A_0. While this does not improve their resolution or SNR, they become comparable to signals recorded afterwards with amplification factor A and can thus be used for quality control.

3.4. Continuously adaptive amplification

In an advanced continuation of the concept of choosing sensor amplification based on calibration bonds, it is also possible to realize a continuously adaptive sensor amplification.

Starting with or without calibration bonds as described above, this system tracks the maximum current amplitude $\hat{\imath}_{\text{max}}$, respectively the maximum raw sensor amplitude $\hat{u}_{s,\max} = \hat{u}_{s,a,\max}/A$ for each joint. After analyzing the current and previous values in a suitable way, e.g. by determining moving average and standard deviation, it adjusts the amplification factor A so that the following sensor signal $u_{s,a}(t)$ has high SNR and good digital resolution while avoiding clipping.

Again, working with the sensor signal amplitude is preferable over working with the current amplitude. It can in fact be advantageous to follow this strategy even with current-controlled processes. For example, assuming normal distribution of $\hat{u}_{s,\max}$, a formula for the amplification factor applied to the next joint can be

$$\mathrm{A} = \mathrm{s}_5 \cdot \frac{u_{\text{ADC, max}}}{\operatorname{movmean}(\hat{u}_{s,\max}) + 6 \cdot \operatorname{movstd}(\hat{u}_{s,\max})} \tag{10}$$

with $s_5 = 0.95$ and $\operatorname{movmean}(\,)$, resp. $\operatorname{movstd}(\,)$ being calculated over a set number of previous joints.

4. Conclusion

There are various strategies for adaptive amplification of piezoelectric vibration sensor signals in ultrasonic joining processes. Most have individual advantages and disadvantages, and typically signal-to-noise ratio (SNR) and digital resolution can be improved if more data is available and more calculation effort is invested. But the small additional improvement is often not worth the extra effort and more complex use, as even rather simple strategies offer a great improvement over static amplification, especially for current-controlled processes. Such a strategy will thus soon be available in Hesse Mechatronics wire bonders and smart welders.

References

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Hesse Mechatronics

Hesse GmbH, founded in 1995 and based in Paderborn, Germany, develops and manufactures fully automatic ultrasonic and thermosonic wire bonding and welding machines as well as laser welding systems together with customized automation solutions for the semiconductor backend industry. Hesse GmbH is one of the world’s leading producers of fully automated wedge-wedge wire bonders and supports customers with the development and optimization of production processes. Software for monitoring the bond processes and customized tools and machines complete the portfolio.

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