Accuracy analysis of the measuring structure with an auxiliary correcting channel

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We considered two-channel measurement structure, which channels operate at different frequencies. Analysis of mutual influence on operation of channels and conclusions concerning the specific structure eddy current thickness-meter of steel sheet constructions are done.

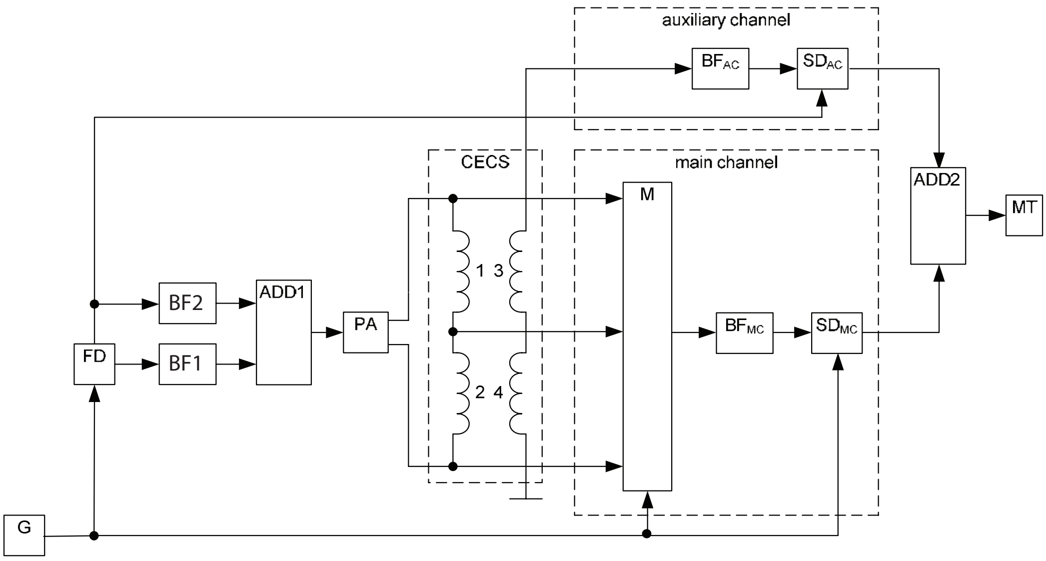
Keywords: two-channel measurement structure, mutual influence, eddy currents, auxiliary measurements method, accuracy analysis

An auxiliary measurements method is one of the methods of correction the uninformative factors influence to the overall measurements result. It is based on extracting of error caused by the influence of these factors, and using it to correct measuring device transfer function. In particular, it can be done by separate measuring of each uninformative factors and subtracting the results of these measurements from the general result [1].

Two-channel measurement structure

Fig. 1 shows a measuring structure, in which the method of auxiliary measurements presented.

We used the following designations: G – rectangular pulse generator with 2 off-duty factor; FD – frequency divider; BF1 and BF2 – band filters, that emit harmonic signals lower and higher frequencies; ADD1, ADD2 – adders; PA – power amplifier; CECS – combined eddy-current sensor, ie it is parametric (1, 2 coils) and transformer (coils 1–4) simultaneously [2]; M – modulator; BF_{MC} and BF_{AC} – band filters main and auxiliary channel; SD_{MC} and SD_{AC} – synchronous detectors main and auxiliary channel; MT – measuring transducer. Modulator M, filter BF_{MC} and synchronous detector SD_{MC} maked up measuring channel, and BF_{AC}, SD_{AC} maked up auxiliary channel.



Rys. 1. Struktura pomiarowa z pomocniczym kanałem korekcyjnym

Fig. 1. Measuring structure with an auxiliary correcting channel

For example, it can be used for building dual-frequency thickness-meter of sheet steel constructions, which reduce the influence of lift-of between the steel constructions and CECS.

The lower and higher frequence signals from the output of BF1 and BF2 filters are added by the ADD1 and amplified by the power amplifier, and then excited to the primary coils of the CECS. Signals from the parametric parts of the CECS coming into the main measurement channel, and signals from the transformer parts coming into the auxiliary channel. As a result, higher frequency signal is in the main channel and may affect its work and vice versa, lower frequency signal is in the auxiliary channel and can affect work of auxiliary channel also. The evaluation of these effects is not obvious and it requires analysis.

Analysis of higher frequency signal's impact to the main channel work

In this case, the primary coils voltage of CECS can be applied as follows:

$$u_1(t) = U_1 \sin(\omega t + \phi_1) + \alpha U_1 \sin(m\omega t + m\phi_1'),$$

$$u_2(t) = U_2 \sin(\omega t + \phi_2) + \alpha U_2 \sin(m\omega t + m\phi_2'),$$

where U_1, U_2 – accordingly amplitude of voltage on coils 1 and 2 of CECS on lower frequency ω,
m – higher to lowest frequency ratio,
a – amplitude of higher frequency signal to amplitude of lower frequency signal ratio,
ϕ_1, ϕ_2 – initial phase of low frequency signals according on coils 1 and 2 of CECS,
ϕ'_1, ϕ'_2 – initial phase of higher frequency signals according on coils 1 and 2 of CECS.

On the output of main channel amplitude-phase modulator M the signal can be evaluate:

$$\begin{aligned}
U_M(t) &= K_M \frac{U_1+U_2}{2}\left[1+\frac{U_1-U_2}{U_1+U_2}\cdot sign\sin(\Omega t+\phi)\right]\cdot\sin\left\{\omega t+\frac{\phi_1+\phi_2}{2}\left[1+\frac{\phi_1-\phi_2}{\phi_1+\phi_2}\cdot sign\sin(\Omega t+\phi)\right]\right\}+\\
&+\alpha K_M \frac{U_1+U_2}{2}\left[1+\alpha\frac{U_1-U_2}{U_1+U_2}\cdot sign\sin(\Omega t+\phi)\right]\cdot\sin\left\{m\omega t+m\frac{\phi_1'+\phi_2'}{2}\left[1+m\frac{\phi_1'-\phi_2'}{\phi_1'+\phi_2'}\cdot sign\sin(\Omega t+\phi)\right]\right\}=\\
&= K_M\left\{\frac{U_1+U_2}{2}\sin\left\{\omega t+\frac{\phi_1+\phi_2}{2}+\frac{\phi_1-\phi_2}{2}\cdot sign\sin(\Omega t+\phi)\right\}+\frac{U_1-U_2}{2}\cdot sign\sin(\Omega t+\phi)\cdot\sin\left\{\omega t+\frac{\phi_1+\phi_2}{2}+\frac{\phi_1-\phi_2}{2}\cdot sign\sin(\Omega t+\phi)\right\}\right\}+\\
&+\alpha K_M\left\{\frac{U_1+U_2}{2}\cdot\sin\left\{m\omega t+m\frac{\phi_1'+\phi_2'}{2}+m\frac{\phi_1'-\phi_2'}{2}\cdot sign\sin(\Omega t+\phi)\right\}+\right.\\
&\left.+\frac{U_1-U_2}{2}\cdot sign\sin(\Omega t+\phi)\cdot\sin\left\{m\omega t+m\frac{\phi_1'+\phi_2'}{2}+m\frac{\phi_1'-\phi_2'}{2}\cdot sign\sin(\Omega t+\phi)\right\}\right\}
\end{aligned} \tag{1}$$

where $(U_1 – U_2)$ – measured amplitude difference, ϕ – initial phase of modulation signal, Ω – modulation frequency, K_M – modulator transfer coefficient, $sign\sin(\Omega t + \phi)$ – managing output signal of the generator G.

After trigonometric transformations of expression (1) and considering that,

$$sign\sin(\Omega t+\phi) = \frac{4}{\pi}\sum_{n=1}^{\infty}\frac{\sin(2n-1)(\Omega t+\phi)}{(2n-1)}$$

we get:

$$\begin{aligned}
U_M(t) &\cong K_M\frac{U_1-U_2}{2}\cdot\left\{\frac{2}{\pi}\left(\cos(\Omega t+\phi-\omega t-\frac{\phi_1+\phi_2}{2})-\cos(\Omega t+\phi+\omega t+\frac{\phi_1+\phi_2}{2})\right)\cos\frac{\phi_1-\phi_2}{2}+\right.\\
&\left.+\frac{8}{\pi^2}\left(\cos(\omega t+\frac{\phi_1+\phi_2}{2})-\frac{1}{2}\left(\cos(2\Omega t+2\phi-\omega t-\frac{\phi_1+\phi_2}{2})+\cos(2\Omega t+2\phi+\omega t+\frac{\phi_1+\phi_2}{2})\right)\right)\sin\frac{\phi_1-\phi_2}{2}\right\}+\\
&+K_M\frac{U_1+U_2}{2}\left\{\sin(\omega t+\frac{\phi_1+\phi_2}{2})\cos\frac{\phi_1-\phi_2}{2}+\frac{2}{\pi}\left(\sin(\Omega t+\phi+\omega t+\frac{\phi_1+\phi_2}{2})+\sin(\Omega t+\phi-\omega t-\frac{\phi_1+\phi_2}{2})\right)\sin\frac{\phi_1-\phi_2}{2}\right\}+\\
&+\alpha K_M\frac{U_1-U_2}{2}\left\{\frac{2}{\pi}\left(\cos(\Omega t+\phi-m\omega t-m\frac{\phi_1'+\phi_2'}{2})-\cos(\Omega t+\phi+m\omega t+m\frac{\phi_1'+\phi_2'}{2})\right)\cos m\frac{\phi_1'-\phi_2'}{2}+\right.\\
&\left.+\frac{8}{\pi^2}\left(\cos(m\omega t+\frac{\phi_1'+\phi_2'}{2})-\frac{1}{2}\left(\cos(2\Omega t+2\phi-m\omega t-m\frac{\phi_1'+\phi_2'}{2})+\cos(2\Omega t+2\phi+m\omega t+m\frac{\phi_1'+\phi_2'}{2})\right)\right)\sin m\frac{\phi_1'-\phi_2'}{2}\right\}+\\
&+\alpha K_M\frac{U_1+U_2}{2}\left\{\sin(m\omega t+m\frac{\phi_1'+\phi_2'}{2})\cos m\frac{\phi_1'-\phi_2'}{2}+\right.\\
&\left.+\frac{2}{\pi}\left(\sin(\Omega t+\phi+m\omega t+m\frac{\phi_1'+\phi_2'}{2})+\sin(\Omega t+\phi-m\omega t-m\frac{\phi_1'+\phi_2'}{2})\right)\sin m\frac{\phi_1'-\phi_2'}{2}\right\}
\end{aligned}$$

Lets we will define how band filter BF_{MC} reduced the amplitude of the signal with $\Omega+m\omega$ frequency.

First we determine the distance between the required frequency ω_r and the frequency cutoff ω_c (in decades) on the frequency axis of filter's LAFC (logarithmic amplitude-frequency characteristic), to determine the signal reducing on the required frequency ω_r:

$$l = \log_{10}\frac{\omega_r}{\omega_c}[\mathrm{d}ec]$$

Signal reducing k_{red} (dB) on the required frequency obtained by the multiplying this distance l on the slope S of filter's logarithmic characteristics:

$$-20\log_{10} k_{red} = l\cdot s = s\cdot\log_{10}\frac{\omega_r}{\omega_c}[dB]$$

Hence:

$$k_{red} = 10^{-\frac{s}{20}\log_{10}\frac{\omega_r}{\omega_c}} \qquad (2)$$

Taking into account the previous formula and having accepted that the maximum reduced error (it called forth the higher frequency) can not be greater than $\delta_{max} = \alpha\cdot 100$ %, we can write the expression for the reduced error due to the filter:

$$\delta_{ref} = \frac{\delta_{max}}{k_{red}} = \frac{\alpha\cdot 100\%}{k_{red}} = \frac{\alpha\cdot 100\%}{10^{-\frac{s}{20}\log_{10}\frac{\omega_r}{\omega_c}}} \qquad (3)$$

For example, the eddy current thickness-meter of sheet steel constructions based on the above measurement structure will be considered. Its main channel uses $\omega=2\pi$ rad frequency, and auxiliary channel uses $m\omega=2\pi\cdot 512$ rad. Auxiliary channel is used to reduce the influence of lift-of between CECS and steel plate to result of the thickness steel plate measurement by the main channel. Modulation frequency Ω is much larger than the working frequency of the main channel and it equals $\Omega = 2\pi\cdot 2048$ rad. So, $\Omega + m\omega = 2\pi\cdot 2560$ rad.

Let us consider that the filter BF_{MC} is 2-order filter with multiloop negative feedback and Q=100 quality factor [3], which set $\omega_r=2\pi\cdot 2048$ rad operating frequency. In this case, the frequency cutoff is

$$\omega_c = \frac{\omega_r}{2Q} = \frac{2\pi\cdot 2048}{2\cdot 100} = 2\pi\cdot 10{,}24 \ \text{ rad.}$$

It is known [3] that LAFC slope at frequencies above the cutoff frequency is –40 dB/dek in 2-order filter. So, from (3) we received (for $\alpha=0{,}1$, $\omega_{sh}=\Omega+\mathrm{m}\omega=2\pi\cdot 2560$ rad):

$$\delta_{ref} = \frac{\alpha\cdot 100\%}{10^{-\frac{s}{20}\log_{10}\frac{\omega_r}{\omega_c}}} = \frac{0{,}1\cdot 100\%}{10^{-\frac{-40}{20}\log_{10}\frac{2\pi\cdot 2560}{2\pi\cdot 10{,}24}}} = 1{,}6\cdot 10^{-4}\%$$

For such structure the error is second order small, ie it can be neglected.

Analysis of low frequency signal's impact to the auxiliary channel work

The analysis will begin with the consideration that at 3 coil of CECS is voltage

$$u_1'(t) = k_{13}U_1\sin(\omega t+\phi_1) + \alpha k_{13}' U_1\sin(m\omega t + m\phi_1'),$$

and at 4 coil is voltage

$$u_2'(t) = k_{24}U_2\sin(\omega t+\phi_2) + \alpha k_{24}' U_2\sin(m\omega t + m\phi_2')$$

where k_{13} and k_{13}', k_{24} and k_{24}' – the transformation coefficient between 1 and 3 and 2 and 4 coils of CECS for ω and $m\omega$ frequency.

At that the signal at the input of auxiliary channel band filter BF_{AC} will be:

$$U_{3-4}(t)=u_1'(t)-u_2'(t)=k_{13}U_1\sin(\omega t+\phi_1)+\alpha k_{13}' U_1\sin(m\omega t+m\phi_1')-$$
$$-k_{24}U_2\sin(\omega t+\phi_2)+\alpha k_{24}' U_2\sin(m\omega t+m\phi_2')$$

We write an expression for maximum reduced error, provided that these harmonics are in antiphase and having accepted that the maximum reduced error will be determined by the ratio of harmonics amplitudes of higher and lower frequencies:

$$\delta_{max} = \frac{k_{13}U_1 - k_{24}U_2}{\alpha k_{13}' U_1 - \alpha k_{24}' U_2}\cdot\frac{1}{k_{red}}\cdot 100\% \qquad (4)$$

Assume that $k_{13}=\beta k_{24}$ and $k_{13}'=\beta k_{24}'$ (where β – relative inequality of transformation coefficient), then expression (4) is written as:

$$\delta_{max} = \frac{\beta k_{24}U_1 - k_{24}U_2}{\beta k_{24}' U_1 - k_{24}' U_2}\cdot\frac{1}{\alpha\cdot k_{red\omega}}\cdot 100\%$$
$$= \frac{k_{24}(\beta U_1 - U_2)}{k_{24}'(\beta U_1 - U_2)}\cdot\frac{1}{\alpha\cdot k_{red\omega}}\cdot 100\% = \frac{\beta'}{\alpha\cdot k_{red\omega}}\cdot 100\%$$

where

$$\beta' = \frac{k_{24}}{k_{24}'}$$

Substituting reducing coefficient from (2), we get:

$$\delta_{max} = \frac{\beta'}{\alpha\cdot 10^{-\frac{s}{20}\log_{10}\frac{\omega_r}{\omega_c}}}\cdot 100\% \qquad (5)$$

Let us consider that the filter BF_{AC} is 2-order filter with multiloop negative feedback, which set $\omega_r=2\pi\cdot 512$ rad operating frequency, with

$$\omega_c = \frac{\omega_r}{2Q} = \frac{2\pi\cdot 512}{2\cdot 100} = 2\pi\cdot 2{,}56$$

rad frequency cutoff and $Q=100$ quality factor. We can calculate the maximum reduced error (5) for $\alpha=0{,}1$ and $\beta'=0{,}015$ ($k_{24}=0{,}004$ and $k_{24}'=0{,}27$ was obtained experimentally, so $\beta'=0{,}004/0{,}27=0{,}015$):

$$\delta_{\max} = \frac{\beta'}{\alpha \cdot 10^{-\frac{s}{20}\log_{10}\frac{\omega_r}{\omega_c}}} \cdot 100\% = \qquad (6)$$

$$= \frac{0{,}015}{0{,}1 \cdot 10^{-\frac{-40}{20}\log_{10}\frac{2\pi\cdot 512}{2\pi\cdot 2{,}56_z}}} \cdot 100\% = 3{,}77 \cdot 10^{-4}\%$$

Expression (6) shows that the error called forth by the influence of main channel frequency signal to auxiliary channel can also be neglected.

Conclusion

Errors called forth by the mutual influence of channels of the thickness-meter measurement structure can be neglected.

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Analiza dokładności struktury pomiarowej z pomocniczym kanałem korekcyjnym

W pracy rozpatrzono dwukanałową strukturę pomiarową, której kanały pracują na różnych częstotliwościach. Wykonano analizę wzajemnego oddziaływania kanałów i otrzymano wyniki dotyczące szczególnej struktury wiroprądowego grubościomierza do badania konstrukcji z blachy stalowej.

Słowa kluczowe: dwukanałowa struktura pomiarowa, oddziaływania wzajemne, prądy wirowe, pomocnicza metoda pomiarów, analiza dokładności

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