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INCREASE OF STRAIN GAGE OUTPUT VOLTAGE SIGNALS ACCURACY USING VIRTUAL INSTRUMENT WITH HARMONIC EXCITATION

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Abstract − This paper describes the principle of harmonic excitation of strain gages in bridge configuration. This system's properties are mathematically determined and measurements are conducted with commutated excitation, AC and harmonic excitation - with and without filtering. The possibility of increasing the accuracy of output bridge voltage measurement by using harmonic excitation is shown.

Keywords: harmonic excitation, resistive bridge, virtual instrument.

1. INTRODUCTION

In measurement of sample deformation strain gages convert sample deformation into the resistance change. This resistance change is usually small (permitted strain gage deformation is 0,1 %), therefore the resistance change is measured in bridge configuration where measured signals are small and noisy. If bridge configuration is excited with higher voltages, the output voltage will be higher for the same measured deformation.

The bridge can be excited with direct or alternating voltage source with certain advantages and disadvantages [1]. The properties of direct voltage excitation can be improved using voltage commutation which can eliminate thermocouple voltages and DC errors. Errors due to noise, power line frequency, its harmonics, offset and offset drifts are more difficult to eliminate in DC excitation systems. The use of AC excitation is a better solution because of lower sensitivity (better immunity) to noise and DC errors (offset) and power line frequency harmonics but it requires the use of more expensive equipment and manipulation with measured signal (filtering and demodulation) [2].

When a higher rate of measurement system data acquisition is required, it is necessary to perform commutation fast enough and if contacts switching time is not shorter than required sample rate this becomes a significant problem.

An important property is also the expected accuracy of measurement system which is greater if the measured signal amplitude is higher. It will be greater if the bridge excitation amplitude is higher, but it is limited by dissipation - heating of strain gages.

By using the harmonic excitation it is possible to achieve higher excitation amplitudes with unchanged heating, similar to the use of impulse excitation. Another advantage of harmonic excitation is in lower required bandwidth and therefore lower contribution of noise to total expected error.

2. PROPOSED APPROACH

When strain gages are excited using voltage source, strain gages are heated (Joule's law) and resistance change achieves stationary state after transient response to change in heating. Maximum voltage of strain gages excitation is defined as the maximum effective voltage which can be applied to the bridge containing strain gage.

Heating of strain gages limits the excitation voltage and therefore also the output voltage obtained by continuous bridge excitation. The second option is to use impulse excitation of strain gages. The excitation and measurement are conducted in time τ which in relation to the period T fulfils the condition $\tau < T$. Similar to the impulse excitation is the application of harmonic excitation. The basic ground of this excitation procedure is the multiplication of AC excitation principle which uses single frequency voltage and is called frequency carrier technique [1].

If more than one frequency carrier is used (two or more) it is possible to achieve a higher amplitude signal while maintaining the same effective value. The total signal is modulated and basically the procedure is similar as to single frequency carrier technique but multiplied. The number of processing segments of band pass filters and demodulation used is equal to the number of frequency carriers. Subsequently, linearly added signals give higher output (measured) signal in comparison to the use of just single frequency carrier.

Advantages of harmonic excitation can be achieved even without the described signal processing (filtering and demodulation), but in this case frequency carriers must have such a phase shift that the amplitudes of all single frequency carriers coincide with amplitude of basic frequency. In that way, the maximum possible amplitude of complex excitation is achieved. Since white noise depends on bandwidth, such solution will have the same noise as in DC system.

2.1. Frequency carrier amplitude and effective value

When using two frequency carriers with frequency f and $3f$, without phase shift, total excitation voltage $u(t)$ is:

$$u(t) = A_1 \sin\left(\frac{2\pi t}{T}\right) + A_2 \sin\left(\frac{3 \cdot 2\pi t}{T}\right) \qquad (1)$$

i.e. its effective value can be calculated using (2).

$$U_{\text{rms}} = \frac{\sqrt{A_1^2 + A_2^2}}{\sqrt{2}} \qquad (2)$$

For n frequency carriers effective value is equal to:

$$U_{\text{rms}} = \frac{\sqrt{A_1^2 + A_2^2 + \ldots + A_n^2}}{\sqrt{2}} = \frac{\sqrt{n} \cdot A}{\sqrt{2}} \qquad (3)$$

i.e. for certain effective value U_{rms} and n frequency carriers of the same amplitude A, where amplitude of each of frequency carriers is calculated using (4).

$$A = U_{\text{rms}} \frac{\sqrt{2}}{\sqrt{n}} \qquad (4)$$

Fig. 1. shows amplitude A of n frequency carriers and for equal effective value of excitation voltage.

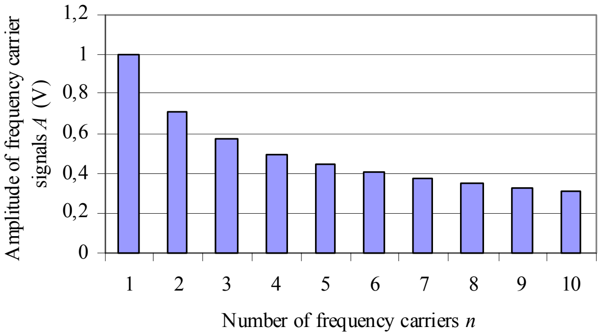

Fig. 1. Amplitude of frequency carrier signals A in dependence to the number of frequency carriers n.

According to calculations, effective value does not depend on frequency or phase shift between frequency carriers so any other combination of frequencies and/or phase shifts gives equal effective value.

2.2. Total amplitude of excitation voltage

Although effective value does not depend on phase shift between frequency carriers, the total waveform changes for different phase shifts. This changes maximum of the total amplitude of excitation voltage and for certain phase shift is equal to the sum of single amplitudes and is equal to:

$$A_{\text{m}} = U_{\text{rms}} \frac{\sqrt{2}}{\sqrt{n}} \cdot n = \sqrt{2} \cdot U_{\text{rms}} \cdot \sqrt{n} \qquad (5)$$

So for example, for three frequency carriers with frequency of f, $3f$ and $5f$, maximum amplitude is achieved with phase shift of φ= 0˚, φ_3= 180˚, φ_5= 0˚. In this case, amplitudes of single sinusoids are at the same position of 90˚ to null value of basic signal, i.e. shift of $T/4$, giving the total amplitude of 1,73 times larger than the amplitude of one frequency carrier with equal effective value.

By increasing the number of frequency carriers, the total maximum amplitude is also increased at a certain point of time at the expense of the remaining part of the period. The impulse excitation effect is achieved, even though continuous harmonic excitation is used.

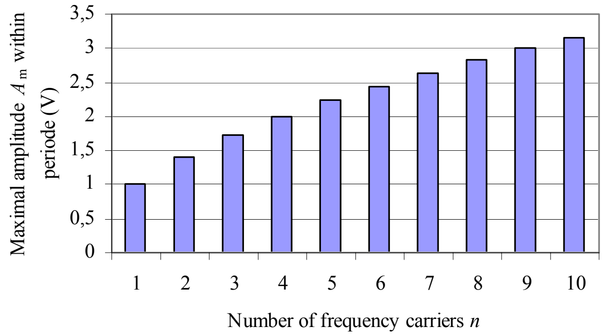

Fig. 2. Dependence of maximum obtained excitation amplitude A_m on the number of frequency carriers n used.

2.3. Total output voltage when using multiple frequency carriers

When bridge is excited with n frequency carriers, the total output voltage u_{o} will be equal to the sum of single responses to each frequency carrier which depends on deformation ε:

$$u_{\text{o}}(t) = \sqrt{n} \cdot \left(\sqrt{2} \cdot U_{\text{rms}}\right) \cdot \varepsilon \cdot \left[\sin\left(\frac{2\pi t}{T_1}\right) + \sin\left(\frac{2\pi t}{T_2}\right) + \ldots + \sin\left(\frac{2\pi t}{T_n}\right)\right] \qquad (6)$$

According to equation (6), it can be concluded that by using multiple frequency carriers, the amplitude of the output signal will be $\sqrt{n}$ times higher when compared with one frequency carrier for the same effective voltage.

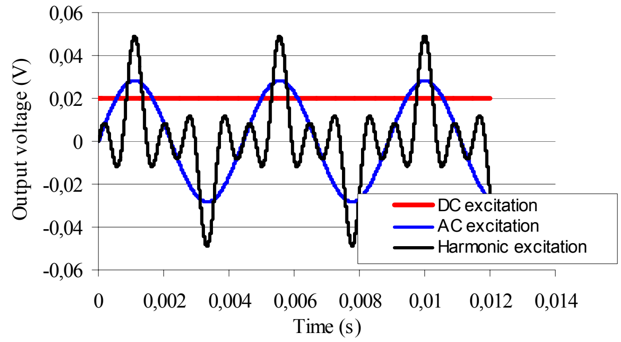

Fig. 3. Output voltage for same effective voltage excitation.

The more frequency carriers are used, the lower single frequency carrier amplitudes will be, to maintain equal effective value of excitation voltage

Fig. 3 shows output voltages for a bridge that is excited with DC, AC and harmonic voltage with equal effective value. AC voltage frequency and base harmonic frequency is equal to 225 Hz. Harmonic excitation consists of frequency carriers of *f*, 3*f* and 5 *f*, with phase shift of φ= 0˚, φ_3= 180˚, φ_5= 0˚.

2.4. Signal to noise ratio

If equal signal processing is applied to output signal as for AC excitation, filtering and demodulation is used. Filtering passes equal bandwidth for each frequency carrier, filtered signals are demodulated and then linearly added.

Total effective value of noise equals to [3]:

$$A_{\text{noise}} = \sqrt{A_{\text{noise }1}^2 + A_{\text{noise }2}^2 + \ldots + A_{\text{noise }n}^2} \tag{7}$$

Total signal to noise ratio equals to:

$$S/N = 20\log\frac{\sqrt{2}\cdot U_{\text{rms}}\cdot\sqrt{n}}{\sqrt{n}\cdot A_{\text{noise }n}} \tag{8}$$

Equation (8) shows that signal to noise ratio does not depend on the number of frequency carriers.

This calculation applies to white noise which occurs in strain gages and with assumption that measurement system has negligible contribution to the overall noise.

2.5. Absolute accuracy

The accuracy of measured voltage using virtual instrument is calculated according to data given by the manufacturer for the used measurement card and it depends on gain and offset errors and their temperature drifts, differential nonlinearity and noise [4]. Error limits are determined by calculating absolute accuracy (AA) according to manufacturer's directions, i.e. absolute accuracy consists of gain error contribution *GE*, offset error *OE* and noise contribution according to (9). Noise contribution depends on effective noise value σ and number of samples *N* which are collected.

$$AA = GE + OE + \frac{3\cdot\sigma}{\sqrt{N}} \tag{9}$$

3. MEASUREMENT SYSTEM

3.1. Implementation of measurement systems

To compare the properties of different excitations to measurement systems, virtual instruments according to Table 1. are implemented.

Measurement system is realised with measurement card NI PCI 6281 and fixed resistance divider according to Fig. 4. This reduces the influence of the amplifier, used for bridge excitation, on measurement results. Fixed resistance divider enables measurement without influences of different heating of single strain gages mounted on a transducer. Therefore, instead of a bridge with some disballance, fixed resistor of fixed "disballance" was used.

Table 1. Description of realized measurement systems.

Implementation	Description
0	Commutated (rectangular) voltage
1	One frequency carrier *f*=225 Hz, *A*=2,5 V, without band pass filter
2	One frequency carrier *f*=225 Hz, *A*=2,5 V, with band pass filter
3	Three frequency carriers *f*, 3*f* (φ=180˚), 5*f*, *f*=225 Hz, A_1=A_2=A_3= $2{,}5\ \text{V}\cdot\sqrt{2}/\sqrt{3}$, without band pass filter
4	Three frequency carriers *f*, 3*f* (φ=180˚), 5*f*, *f*=225 Hz, A_1=A_2=A_3= $2{,}5\ \text{V}\cdot\sqrt{2}/\sqrt{3}$, with band pass filter

Maximum output current of D/A converter is 5 mA and therefore it is not possible to connect output of a D/A converter directly to strain gage bridge with resistances of 350 Ω. Used divider has resistance of R_1=100 kΩ and R_2=10 Ω, i.e. divider ratio is approximately 10000:1 and with voltage source of 2,5 V, current through divider is approximately 25 µA. With DC excitation of 2,5 V bridge imbalance is proportionally smaller according to divider ratio and is approximately 0,25 mV. Measured voltage ratio (output voltage divided to excitation voltage) is approximately 0,1 mV/V. Software generates voltage at the output of the measurement card D/A converter which is connected to divider and the divided voltage is connected to the input of A/D converter. The lowest measurement range of measurement card of ± 100 mV is used.

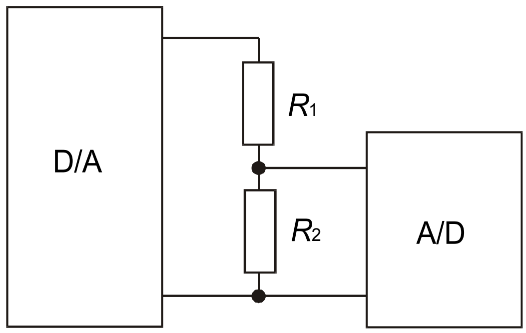

Fig. 4. Measurement configuration.

After data acquisition, filtering (measurement implementation 2 and 4) and rectification of measured signals are conducted. Rectification is implemented by software using function "absolute value". Subsequently, mean or maximum value is determined from certain amount of gathered samples.

Fig. 5. shows block diagrams of signal processing of all implementations. Bandpass filters are implemented using labview filter function as Bessels IIR 8th order filters. Bessels filter has the best step response; no overshoot or undershoot, only a rise time inversely proportional to the filters corner frequency. Bessels filter are suited for applications requiring minimal distortion of fast changing signals [5]

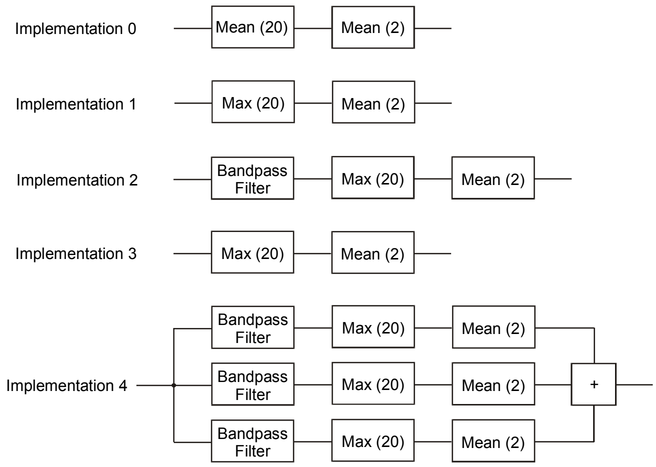

Fig. 5. Block diagram of implementation signal processing.

Some AC measurement systems use frequency carrier of 225 Hz [2], therefore this value is chosen to be the basic frequency of these implementations. Samples are generated with sample rate of 9 kHz and data are acquired using the same sample rate. As sampling is coherent with generated signal the bias is equal to zero [6]. Using this sample rate of generating and acquiring data, 40 samples are acquired within the duration of one period of base frequency carrier.

In commutated excitation, mean value from 20 positive and then 20 negative samples is calculated, and subsequently mean value of the positive and negative part of period is calculated. For other excitations, maximum value from 20 samples of positive and negative part of period is determined, and then mean value is calculated. From every 40 collected samples, one sample containing information of measured disballance is obtained.

The described procedure of sample acquisition and data processing gives samples that represent envelope plotted by harmonic excitation frequency carriers.

3.2. Accuracy of measured voltage using virtual instrument

Contribution of noise to error depends on the number of samples and on/off state of the 40 kHz low pass filter within measurement card. The filter was on for all measurements to reduce the effective value of measurement card noise from 9 to 2 μV.

For steady DC signals, measurement card absolute accuracy is within the range of 13,6 to 28,3 μV for measured voltages from 0 to 100 mV and for 100 samples averaging. Gain error is equal to 147 ppm of measured value i.e. up to 14,7 μV for 100 mV. Offset error is equal to 132 ppm of measurement range i.e. 13,2 μV. Noise contribution is equal to 6 μV for single sample and decreases with square root from sample number. Calculating absolute accuracy for each measured voltage, measurement uncertainty can be determined as B type where absolute accuracy is divided with $\sqrt{3}$ (rectangular distribution).

Since all implementations periodically change voltage excitation polarity and during signal processing positive and negative part of measured amplitude is averaged, it can be concluded that offset error is cancelled out. Remaining contribution is gain error, which depends on measured amplitude and noise contribution which is constant. For each measurement with noise contribution larger than gain error contribution, the dominant part will be noise contribution. This is the case when small voltages are measured.

Calculated absolute accuracy is shown in Fig. 6. and Fig. 7. as vertical bounded lines. In Fig. 6, absolute accuracy is calculated for two samples per base carrier frequency periode. In Fig. 7, absolute accuracy for commutated excitation is calculated for 40 samples, which lowers noise contribution.

For n frequency carriers, $\sqrt{n}$ times larger amplitude is measured. Measured value is also $\sqrt{n}$ time larger, therefore both measured value and error limits should be divided with $\sqrt{n}$. Since the increase of error limits is lower than increase of measured value, measurement error limits and consequently measurement uncertainty are decreased.

According to Fig. 6., the absolute accuracy is decreasing when the number of frequency carriers increases.

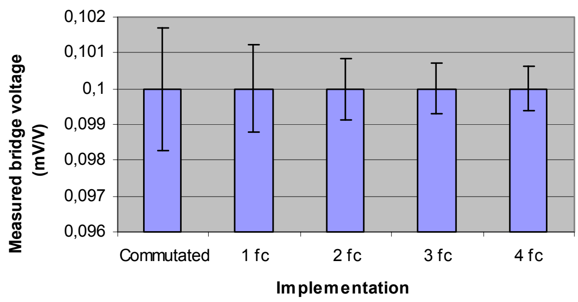

Fig. 6. Absolute accuracy in dependence on the number of frequency carriers

4. RESULTS

It is not possible to conduct measurements simultaneously. Therefore they were conducted sequentially within the shortest possible time period. This reduces the possible influence of system components change due to drift and influence of temperature change on results. Measurement results and the corresponding error of output voltage using different systems are presented in Table 2.

Table 2. Measurement results.

Implementation	Number of measurement samples	Measured output voltage (μV)	Absolute accuracy (μV)	Measured voltage ratio (mV/V)	Ratio absolute accuracy (μV/V)
0	40	252,3	0,99	0,1009	0,4
1	2	357,2	4,29	0,1012	1,2
2	2	356,2	4,29	0,1008	1,2
3	2	617,9	4,33	0,1009	0,7
4	2	614,8	4,33	0,1004	0,7

Voltage on measurement card input is $\sqrt{2}$ times larger for excitation with one frequency carrier and $\sqrt{6}$ times larger for measurement with three frequency carriers in comparison with rectangular DC excitation. When output to excitation voltage ratio is calculated, it is necessary to divide the result with $\sqrt{2}$, or with $\sqrt{6}$. Absolute accuracy is also divided with an appropriate factor.

Implementation 3 has absolute accuracy, almost $\sqrt{n}$ times lower than excitation with one frequency. Accuracy improvement is according to previously mention. Implementation 2 and 4 has a lower result which is presented in Fig 7. Lower value is measured due to the influence of digital filtering to measured signals.

When using band pass filters, the influence of filtering on signal amplitude reduction should be taken into account, i.e. correction factor should be applied.

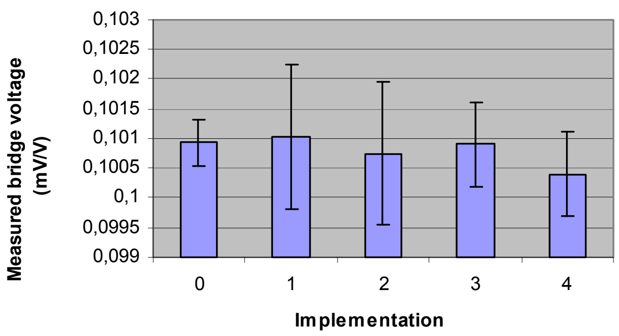

Fig. 7. Measured voltage ratio and absolute accuracy in dependence to implementation.

When output bridge voltage is small, then the increase of signal for $\sqrt{n}$ and almost unchanged absolute accuracy result in maximum possible reduction of absolute accuracy of ratio. For example, for signal of 1 mV and the use of harmonic excitation with three frequency carriers would result in voltage which is $\sqrt{3}$ times larger. Absolute accuracy would be 4,39 μV and 4,49 μV respectively. Measurement result should be divided with $\sqrt{3}$, so absolute accuracy for the second measurement are 4,49 μV/ $\sqrt{3}$ or 2,6 μV.

5. CONCLUSIONS

The use of excitation with multiple frequency carriers increases the accuracy of measured output bridge voltage. This is achieved by increasing voltage in one part of the period at the expense of the remaining part. Measured signal is in the envelope of frequency carriers and measurement of peak values achieved by frequency carriers provides information on true output to excitation voltage ratio.

This procedure is particularly appropriate for small signals where signal increase is more significant and absolute accuracy is slightly increased. In these cases, the improvement according to $\sqrt{n}$ law is achieved.

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