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UNCERTAINTY ANALYSIS OF STRAIN GAGE CIRCUITS

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Abstract: A new topology of strain gage sensor signal conditioner based on the alternative current loop is proposed. The mathematical model of this sensor is discussed and its advantages are revealed. The results of computer simulation confirming the theoretical result are given.
Keywords: Gage sensors, current loop circuit, digital signal processing, Wheatstone bridge, interval analysis.

1. Introduction

Historically, the development of strain gages has followed many different approaches, and gages have been developed based on mechanical, optical, electrical, acoustical and even pneumatic principles [1]. Electrical resistance strain-gauge nearly satisfies all of the optimum requirements for a strain gage; therefore it is widely employed in stress analysis and as the sensing element in many other applications. The minute dimensional change of mechanical elements in response to a mechanical load, pressure, force, and stress causes a change in the resistance of the strain gage.

The bridge circuit has been a standard measurement circuit topology for over a century. Some derivative of it could reliably estimate almost any resistive and reactive electrical quantity when the product of the opposite bridge arm impedances was adjusted to be equal. As an electrical circuit for variable-impedance sensor element signal conditioning, the classic Wheatstone bridge provides a number of well-known

advantages [3]. However, there are important limitations inherent to this circuit [4], namely: 1) only half the signal from each element's impedance change is typically consumed in adjacent bridge arms; 2) the output signal is usually a nonlinear function of impedance change per individual bridge add measurement uncertainty, particularly when they occur in the inter-bridge wiring and especially when the various changes do not evolve identically; 4) the transfer function, including compensation, of a bridge transducer is typically not adjustable after manufacture and installation when the actual operating environment becomes known. Therefore, it is necessary to carry out the previous precise calibration of the gage sensor using the discrete trimming as well as accurate laser trimming techniques [2]. To eliminate the influence of connecting wires and nonlinearity of bridge circuit it was suggested [5] to use the current loop circuit put forward by K.F. Anderson [4]. It allows one to account for the parasitic influence of environmental variations in transducers' resistances as well as the induced noise and to introduce the required corrections into the output signal of this signal conditioner.

2. Analysis using interval arithmetic

In strain measurement, the uncertainty can arise from the process, strain gage, measuring circuits, lead wire and data representation element. In comparison to the classical methods, interval method considers all the sources of uncertainty and estimate in a single step of evaluation [6]. Hence it is proposed that interval method is a viable and alternative tool for uncertainty analysis of strain gage measuring circuits.

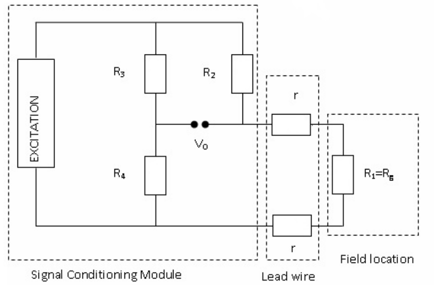

Fig. 1 Strain Measuring circuits (Quarter bridge)

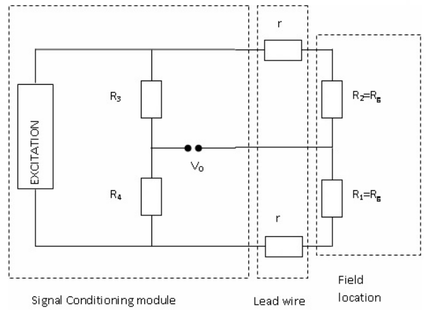

Fig. 2 Strain Measuring circuits (Half bridge)

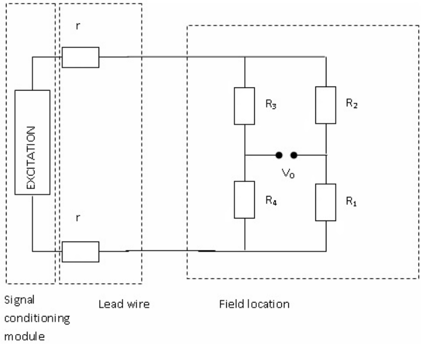

Fig. 3 Strain Measuring circuits (Full bridge)

Quarter bridge arrangement shown in Fig 1 utilizes a single active strain gage in position R_1 and is often employed for both static and dynamic strain measurements if the temperature compensation is not required. The $R_1 = R_G$ and the other three resistances are selected to maximize the circuit sensitivity while maintaining the balance condition $R_1R_3 = R_1R_4$. The performance function with the lead wire resistance (r) is [3]

$$V_0 = \left(\frac{\frac{[V_{in}]}{4} \times \frac{\Delta R_G}{[R]}}{\left(1 + \frac{\Delta R_G}{2[R]} + \left(\frac{[r]}{[R]} \times 2 + \frac{\Delta R_G}{[R]}\right)\right)} \right) \quad (1)$$

The half bridge arrangements shown in Fig. 2, utilizes two active strain gages in position R_1 and R_2 and are denoted as R_G and the performance function is

$$V_0 = \left(\frac{[V_{in}] \times \frac{\Delta R_G}{[R]}}{\left(2(1 + \frac{2[r]}{[R]}\right)} \right) \quad (2)$$

In full bridge configuration, four active strain gages are used as shown in Fig. 3. When the gages are placed on a cantilever beam in bending, with tensile strain on gages 1 and 3 (top surface of the beam) and compressive strain on gages 2 and 4 (bottom surface of the beam), the performance function with lead wire resistance (r) is

$$V_0 = \left(\frac{[V_{im}] \times \left(\frac{\Delta R_G}{[R]}\right)}{\left(1 + \frac{2[r]}{[R]}\right)} \right) \quad (3)$$

where V_0 is the output voltage; V_{in} is the excitation voltage, the resistance of fixed resistors are denoted as $R_1 = R_2 = R_3 = R_4 = R$; r is the lead wire resistance; and ΔR_G

is the change in resistance of stain gage. The performance function of a quarter, half and full bridge strain measuring circuit given in equations (1), (2) and (3) are expressed in the form of natural interval extension function by replacing the uncertain input parameters in interval form.

3. Circuit topology

In this section the modification of the current loop for gage measurements with the utmost accuracy based on the optimal digital signal processing (DSP) is proposed.

The block diagram of proposed signal conditioner based on the current loop is shown on Fig. 4.

In principle, the direct current (DC) source can be used in the loop circuit. Then the output samples of the channel responses can be written as [5], [8]

$$v_{ik} = V_k(t_{ik}) = A_k\psi(t_{ik}) + B_k + \xi_{ik},$$
$$i=1, 2,\dots, N, \quad k=1,2,3,4,R; \quad (4)$$

where A_k is the unknown response amplitude of the k-th channel be estimated from samples v_{ik}; B_k is the DC offset to the signal to be acquired from the k-th channel; t_{ik} are the discrete time moments; ξ_{ik} is the A_k are of interest for us. The offset that requires making the sampled signals positive, but due to zero drifts of operational amplifiers it is assumed to be unknown.

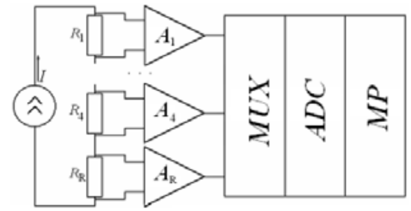

Fig. 4. Gage pressure sensor electric circuit. I is a current source: R_1,…, R_4, R_R and A_1,… A_4, A_R are resistors and amplifiers respectively; MUX is a multiplexer; ADC is an analog-to-digital converter; MP is a microprocessor; index R corresponds to the reference unit.

In order to solve the set (4) for A_k and eliminate the unknown offsets B_k we need to modulate the DC signal in predetermined manner ψ(t) (e.g. as meander line).

After sampling procedure the subsequent digital processing of all responses is performed by the microprocessor. The sampled signals taken from channels can be represented as follows [5], [8]:

$$v_{ik} = V_k(t_{ik}) = A_k\sin[2\pi(f_0 + \lambda)t_{ik} + \varphi_k] + B_k + \xi_{ik},$$
$$i=1, 2,\dots, N, \quad k=1,2,3,4,R; \quad (5)$$

where A_k and φ_k are the unknown amplitude and phase of the k-th channel response to be estimated; λ is the small fluctuation of the central frequency f_0 occurred due to source instability.

The additive noise ξ_{ik} caused largely by the amplifiers thermal noise is implied to be normally distributed with zero mean and unknown variance σ^2. In addition, the value of λ is considered to be very small in comparison with f_0 ($|\lambda / f_0| \le 0.01$). And finally, the values of t_{ik} and t_{im} are not equal for different channels when $k \neq m$. Under these assumptions the set (2) can be solved by the ML method for unknown parameters A_k, φ_k, B_k, and λ [5]. The total number of unknowns is 16.

If the total measuring time does not exceed the several periods of feeding current (e.g. 2-3 periods), the value of $\lambda N\tau \leq 0.15$ (where $\tau = t_{ik} - t_{(i-1)k}$). In this case, the sine and cosine of λt_{ik} can be substituted by their approximations: $\sin\lambda t_{ik} \approx \lambda t_{ik}$ and $\cos\lambda t_{ik} \approx 1$. Then the set (2) can be rewritten after the brackets removal as

$$v_{ik} \approx A_k \sin(2\pi f_0 t_{ik})\cdot\cos\varphi_k + A_k 2\pi\lambda t_{ik}\cos(2\pi f_0 t_{ik})\cdot\cos\varphi_k + B_k +$$
$$+ A_k \cos(2\pi f_0 t_{ik})\sin\varphi_k - A_k 2\pi\lambda t_{ik}\sin(2\pi f_0 t_{ik})\cdot\cos\varphi_k + \xi_{ik},$$
$$i=1, 2, \ldots, N, \quad k=1,2,3,4,R; \quad (6)$$

The solution of analogues seven parameter estimation problem was discussed in [7] where the responses of two channels were processed. This solution is reduced to iteration procedure when the values of unknown parameters A_k, B_k, φ_k are obtained under the assumption that the signal frequency is unknown either and should be estimated jointly with amplitudes, phases and off-sets.

In this estimation problem the signal frequency $f_0 + \lambda$ is approximately known (since $\lambda \ll f_0$). That is why, we use the approach of ML parameter estimation proposed in [5]. The following variable substitution

$$\begin{cases} q_{1k} = A_k \cos\varphi_k, \\ q_{2k} = A_k \lambda\cos\varphi_k, \\ q_{3k} = A_k \sin\varphi_k, \\ q_{4k} = A_k \lambda\sin\varphi_k, \\ q_{5k} = B_k, \end{cases} \quad \text{and} \quad \begin{cases} x_{1ik} = \sin\omega t_{ik}, \\ x_{2ik} = 2\pi t_{ik}\cos\omega t_{ik}, \\ x_{3ik} = \cos\omega t_{ik}, \\ x_{4ik} = -2\pi t_{ik}\sin\omega t_{ik}, \\ x_{5ik} = 1; \end{cases}$$
$$i=1, 2, \ldots, N, \quad k=1,2,3,4,R; \quad (7)$$

makes the set (3) linear for new variables $\boldsymbol{q} = (q_{11},\ldots,q_{51},\ldots,q_{1R},\ldots,q_{5R})^T$ (^{T} the sign designating the transpose matrix)

$$v_{ik} = \sum_{j=1}^{5} q_{jk} x_{jik} + \xi_{ik}, \qquad i=1, 2, \ldots, N, \quad k=1,2,3,4,R; \quad (8)$$

As it follows from (4) and (5), the total number of new variables q_{jk} is equal to 25. Hence, they are to be bound by 9 bilinear relationships, which can be easily found from the set (4):

$$q_{1k} q_{4k} = q_{2k} q_{3k}; \quad \lambda = q_{2k}/q_{1k}; \quad k=1,2,3,4,R; \quad (9)$$

Really, one can find many more relationships between the variables q_{jk}, but only 9 of them are independent.

4. Computer Simulation

The comparative study of the accuracy of proposed statistical estimation technique has been performed using computer numerical simulation. Two series of experiments were made. In the first series, the estimation of A_k was carried out by two different techniques: described in [7] and proposed in this paper. The measuring accuracy is characterized by the standard deviation (STD) of estimating errors. The frequency f_0 = 20 kHz and the sampling rate $f_m = 1/\tau$ was 10 times higher. The value of

frequency variation is chosen from the range of 0 to 200 Hz. The signal-to-noise ratio (SNR) was determined by the value A_k^2/σ^2. Typical results are shown in Fig. 2, which gives the dependences of decimal algorithm lg(STD) of estimating parameter on the decimal logarithm lg(SNR) of SNR obtained by the mentioned estimation methods. As it can be seen from the curves, the method proposed in [6] (curves 2 and 3) has the systematic errors caused by the insufficiently accurate estimation of the frequency variation λ. While the estimation accuracy of the suggested technique (curve 1) is free from these errors and defined only by the SNR.

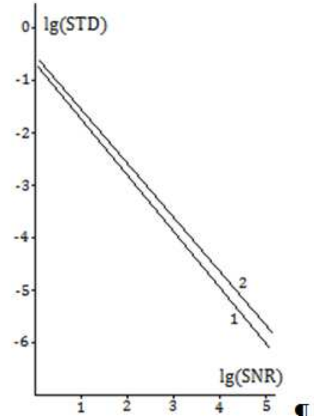

Fig. 5. Dependencies of lg(STD) vs lg(SNR) for two sensor topologies: 1 – four active measurement gauges and the reference one; 2 – only two active elements and one reference gauge.

5. Conclusion

The performance functions of quarter, half and full bridge strain measuring circuits are non-inclusive hence, the narrow width for output voltage of these circuits is obtained by method of moments instead of interval arithmetic.

The relatively new signal conditioner using the alternating current loop circuit is proposed. It has the higher sensitivity as well as measurement accuracy to be compared with the conventional bridge circuits. Moreover, this signal conditioner allows one to diminish considerably the total sensor cost.

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ПРИМЕНЕНИЕ ИНФОРМАЦИОННЫХ ТЕХНОЛОГИЙ ПРИ РАЗРАБОТКЕ ПОДСИСТЕМЫ ОТОБРАЖЕНИЯ ТЕХНОЛОГИЧЕСКОЙ ИНФОРМАЦИИ О СОСТОЯНИИ ОБОРУДОВАНИЯ ГЭС

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Комплексное внедрение информационных технологий в промышленную сферу является одной из зон пристального внимания как государства, так и частных компаний. Особенно это актуально для объектов гидроэнергетики, где сосредоточено большое количество оборудования, управлять которым необходимо в режиме реального времени.

Процесс сбора полной информации о работе оборудования гидроэлектростанции (ГЭС) является трудоемким процессом, требующим больших затрат времени, хотя с точки зрения пользователя эта задача сводится к простой формуле: получать для дальнейшей обработки необходимую информацию в нужное время, в нужном виде, в конкретном месте компьютерной сети предприятия. Решение задачи, описываемой этой формулой, требует подбора аппаратно-программной платформы, модернизации и/или создания подсистем управления технологическими процессами, контроля и учета энергоресурсов и других подсистем основного и вспомогательного

производства, в частности, разработки единого способа отображения технологической информации о состоянии оборудования ГЭС.

Решение задачи унификации способа отображения информации о состоянии объектов ГЭС становится тем более актуальной, чем большее количество различных автоматизированных систем управления технологическими процессами (АСУ ТП) объединяется в единую сеть для обмена информацией.

Разработанная авторами подсистема позволяет отображать технологическую информацию о состоянии оборудования, собранную из разных АСУ ТП, в виде однотипных мнемосхем, таблиц, сообщений и трендов на одном автоматизированном рабочем месте, а также унифицировать отображение объектов мнемосхем.

Основными функциями подсистемы являются:

1) отображение процессов выработки, перетоков и распределения электроэнергии как в обобщенном виде (с помощью зон индикации в пунктах меню и на мнемосхемах), так и для частных параметров (их индикация на мнемосхемах при получении сообщений о выходе параметра за границу аварийной или предупредительной уставки или возникновении неисправности), а также есть возможность работать с оперативными сообщениями и с архивом сообщений;
2) загрузка значений параметров и сообщений из базы данных центра сбора и обработки данных (ЦСОД);
3) запись операций диспетчера, регламентированных системой (квитирование сообщений, выдача команд) в архив ЦСОД.

На рис. 1 представлена главная экранная форма подсистемы (оперативный уровень), позволяющая контролировать текущее состояние основного оборудования станции (гидроагрегатов, трансформаторных групп, открытых распределительных устройств).

На главной форме пользователю доступны следующие функции:

1) управление выбором и просмотром мнемосхем с помощью меню;
2) сохранение мнемосхем в формате *.png;
3) печать мнемосхем;
4) просмотр и квитирование (подтверждение приема) оперативных сообщений, формируемых в информационной среде ГЭС;
5) просмотр основной и детальной информации о параметре мнемосхемы;
6) «быстрый» просмотр сообщений и значений параметра в графическом виде (на рис. 2 приведен пример окна для просмотра трендов) и в виде таблицы; имеется возможность фильтрации данных по времени и настройки отображения кривых тренда (рис.3) и сохранение полученных данных в файлы различных форматов (графика в формате *.png, таблицы значений в формате *.csv);
7) просмотр основных показателей ГЭС;