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A Novel Automatic Multi-point Multi-channel Shunt Calibration System for Field Calibration of Strain-gauge Based Transducers in Time Critical Applications

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Abstract—*Static testing of aerospace propulsion systems requires extensive instrumentation where a number of strain gauge based transducers are used to measure pressure, thrust and strain for performance evaluation, qualification and acceptance of these systems. Conventional method of field calibration of these transducers by bringing the standards to the test bed is time consuming, cumbersome, error prone and sometimes not at all feasible. As an effective alternative, we have conceptualized a novel automatic multi-point multi-channel shunt calibration system for field calibration. Prototype of a microcontroller based automatic shunt calibration system (ASCS) has been designed, developed and tested to prove the concept. We have carried out 3/5/7/11 point shunt calibration of up to 16 channels. Maximum error in calibration was found to be 0.888% of full scale output. This has enabled us to automate the complete field calibration process and reduce the overall calibration time by more than 90% with respect to the manual process, thereby making it preferable for time critical applications. The system can be modified for further reduction in calibration time, improvement in accuracy and increase in channel count.*

1. INTRODUCTION

Strain-gauge based transducers, like pressure transducers and load cells, are extensively used for measurement of pressure and force in a variety of industrial, aerospace, defence and general purpose applications [1]. During static testing of aerospace propulsion systems, these transducers are used to measure chamber pressure and thrust which are very crucial for ballistic performance evaluation [2]. These transducers require periodic calibration to ensure their suitability for usage. Laboratory calibration of these transducers is carried out using standard calibration set-up under controlled environment [3, 4]. When these transducers are used in actual field, they become part of a different measurement set-up in a different environment. This necessitates the calibration of the complete measurement chain including the transducer. This is called field calibration or in-situ calibration which should be carried out by bringing the corresponding standard to the field to apply the required measurand. Necessary corrections must be applied to take care of the effects of field environment. This method of field calibration is quite cumbersome, time consuming, expensive, and prone to systematic and human error and most of the time it is not at all feasible. Hence this method of field calibration is not fit for time critical, cost effective and highly accurate measurements. An effective alternative to this approach is shunt calibration where required levels of measur and are electrically simulated by shunting one arm of the transducer's Wheatstone bridge with a high precision resistor [5, 6]. Corresponding bridge outputs are acquired by a data acquisition system. This set of inputs and outputs are processed and analyzed to ensure the suitability of the complete measurement and to find out the overall scale factor or the look-up table for converting the voltage outputs into corresponding engineering units. This method of field calibration is carried out without bringing the standard to the field and hence completely avoiding the paraphernalia associated with it. Shunt calibration can be carried out without un-mounting the transducers from the test article. All these advantages have made the shunt calibration method as the preferred method of field calibration. But in this method also connectivity has to be established manually with the appropriate shunt resistors which are usually arranged in a shunt box for simulating various levels of the measurand. If calibration of another channel is required, then it has to be done either by using a separate shunt box or by removing the currently used shunt box from the previous channel and connecting it to the new channel. Further, if the number of simulation levels of the measurand is more or multiple channels are involved, then either more number of shunt boxes will be required or substantial amount of time has to be spent for establishing connectivity. This is detrimental from time criticality and resource optimization points of view. Hence we have conceptualized, designed and developed a novel automatic shunt calibration system (ASCS) consisting of the shunt calibration hardware and corresponding software capable of carrying out multi-point and multi-channel shunt calibration. With substantial reduction in calibration time, ease of implementation and minimum resource requirements, this system is going to enhance our capability to meet the field calibration needs in time critical applications.

2. 2. PRINCIPLE

Strain gauge based transducers, like pressure transducer and load cells, use four strain gauges which are electrically connected as the four arms of a Wheatstone bridge [7, 8]. Fig. 1 shows the picture of a strain gauge based pressure transducer, physical placement of the strain gauges on the diaphragm and their corresponding electrical connectivity in the form of a Wheatstone bridge.

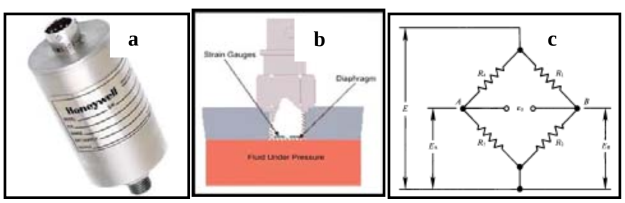

Fig. 1: a. Honeywell make Strain gauge based pressure transducer, b. Strain gauges bonded on the diaphragm, c. Electrical connectivity of 4 Strain gauges as the 4 arms of a Wheatstone bridge

The bridge is excited by an external DC voltage source. In the absence of the measurand (pressure or force in case of a load cell), the bridge is balanced and output of the bridge is zero. In response to the measurand, two strain gauges experience tensile strain and the remaining two experience compressive strain. The bridge gets unbalanced and gives non-zero output. This output is proportional to the measurand in the linear operating range of the transducer. In laboratory calibration of the transducer, dead weights are used to physically apply different levels of measurand to the transducer [9-11]. Applied levels of the measurand and the corresponding bridge outputs are used to generate the scale factor and other calibration related parameters like linearity, repeatability and hysteresis. When the transducer becomes part of a complete measurement chain in field applications, the laboratory calibration results do not hold good any more. Field calibration of the transducers, along with the complete measurement chain, must be carried out. The most convenient and effective way to do this is by shunt calibration. Here different levels of the measurand are electrically simulated by unbalancing the Wheatstone bridge in a predefined way. This is achieved by shunting various values of resistors across one arm of the Wheatstone bridge as shown in Fig. 2.

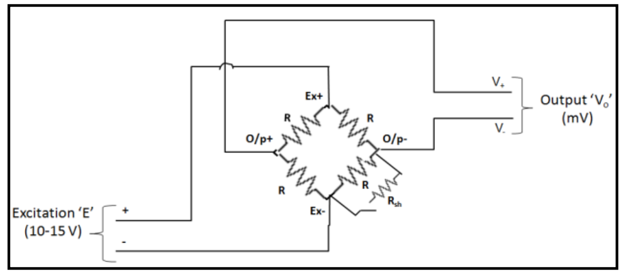

Fig. 2: Principle of Shunt calibration: A shunt resistor is connected across one arm of the bridge to electrically simulate a specific level of measurand.

Analysis of the Wheatstone bridge and the methodology to find out various shunt resistors to simulate different levels of the measurand are explained below:

As shown in Fig. 2, the bridge with a DC excitation of 'E' (Volts), bridge resistance of 'R' (Ohms), without shunting, is balanced. Hence bridge output is zero.

$$V_O = V_+ - V_- = E\frac{R}{R+R} - E\frac{R}{R+R} = \frac{E}{2} - \frac{E}{2} = 0 \qquad .(1)$$

With the connection of a shunt resistor across one arm, the bridge gets unbalanced electrically. V_+ remains unchanged at $\frac{E}{2}$, but V_- changes to:

$$V_- = E\frac{(R \,||\, R_{sh})}{R+(R||R_{sh})} = E\frac{R_{sh}}{R+2R_{sh}} \,. \qquad .(2)$$

Hence the bridge output is given by:

$$V_o = V_+ - V_- = \frac{E}{2} - \frac{E*R_{sh}}{R+2R_{sh}} = \frac{E*R}{2(R+2R_{sh})} \qquad .(3)$$

It can be observed from equation-3 that by varying the resistance of the shunt resistor, the bridge output can be changed. Thus different levels of measurand can be electrically simulated by using different shunt resistors to give desired levels of the bridge output. Equation-4 gives the expression to find out R_{sh} for simulating a specific level of the bridge output.

$$R_{sh} = R * \frac{0.5E - V_o}{2V_o} \qquad (4)$$

For N-point (N-1 steps) calibration, shunt resistances can be calculated to give various levels of output. For *N*-point calibration, V_o can be taken as 0, $\frac{V_{FS}}{N-1}$, $\frac{2\,V_{FS}}{N-1}$, $\frac{3\,V_{FS}}{N-1}$,, V_{FS} , where V_{FS} is the full scale output of the transducer with the rated value of the measurand.

This technique can be applied to a variety of field calibration cases as given below:

- Case-1: Single step calibration of a single transducer (can be carried out by connecting only one shunt resistor)
- Case-2: Multi-step (N-point) calibration of single transducers (can be carried out by using *N-1* different values of shunt resistors, connecting one at a time. *'N-1'* no. of connections and disconnections have to be made, hence requires more calibration time.)
- Case-3: Single step calibration of multiple (*M* nos.) transducers (can be carried out by using *M* nos. of shunt resistors, one for each transducer. *M* nos. of connections and disconnections are required.)
- Case-4: Multi-step *(N*-point) calibration of multiple *(M)* transducers (can be carried out by using M nos. of *N-1* type of shunt resistors. *M(N-1)* nos. of connections and disconnections have to be made, which is quite cumbersome and time consuming)

Manually carrying out shunt calibration for case-1 and case-2 with small value of N is convenient, but becomes very much complex, time consuming and inefficient in case-3 and case-4. Being an electrical simulation technique, shunt calibration provides the opportunity to adopt and apply this concept for automation by innovative implementation. Automation of shunt calibration can provide minimization of manpower and hardware requirements, drastic reduction in number of connections and disconnections and substantial reduction in calibration time.

3. DESIGN

During static testing of aerospace propulsion systems, a number of strain gauge based pressure transducers and load cells are used. The pressure and thrust data are used for performance evaluation of the propulsion systems. These transducers use metallic strain gauges of resistance 350Ω with a sensitivity of 3mV/V for rated value of the measurand (pressure or thrust). With an excitation of 10V DC and rated pressure (or thrust), they give a full scale output of 30mV. We usually carry out 3-point/5-point/ 7-point/11-point calibration depending upon the specific field application and accuracy requirements. Block diagram of the automatic shunt calibration system for carrying out multi-point calibration of up to 16 transducers (including the measurement chain) is shown in Fig. 3.

A set of resistors, which are required for simulating different levels of measurand and give corresponding levels of bridge output, forms a resistor bank. Values of these resistors are calculated using equation-4. This resistor bank is interfaced to a resistor selection circuit. There is a channel selection circuit which can interface up to 16 transducers (channels) to the ASCS. A micro-controller is used to generate the channel selection and resistor selection logic. A Calibration Control Computer (CCC) controls the overall calibration process. The electrical interface diagram is shown in Fig. 4. The hardware connectivity for resistor selection and channel selection are established using a pair of 16-channel analog multiplexers (AD7506).

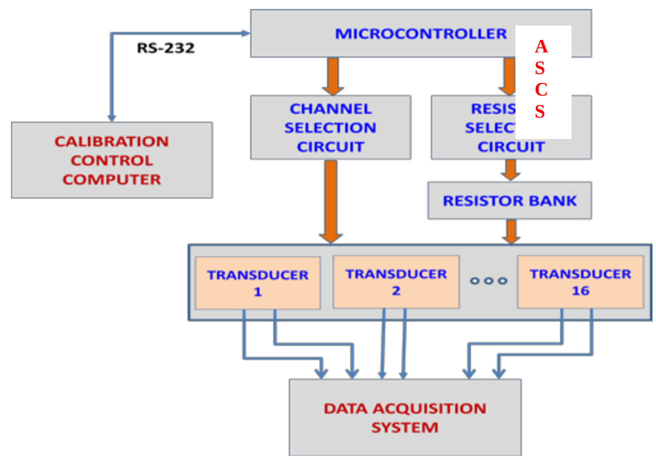

Fig. 3: Block diagram of the Automatic Shunt Calibration System (ASCS)

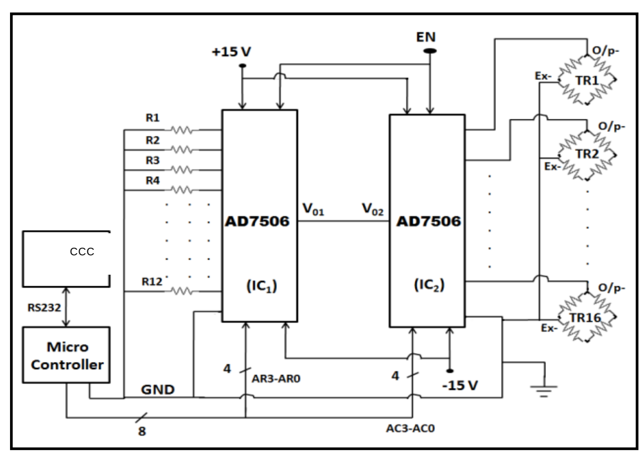

Fig. 4: Circuit diagram for implementation of the of the Automatic shunt calibration system (ASCS). EN-Enable, AR0-AR3 are resistor selection lines and AC3-AC0 are channel selection lines for IC1 and IC2 respectively. TR1, TR2, … TR-16 are the transducers. Outputs of these transducers are connected to a data acquisition system.

IC_1 works as an analog multiplexer to select any one of the resistors from the resistor bank and connects that to the output line. IC_2 is used as a de-multiplexer. The output line of IC_1 is connected to the input line of IC_2. The output lines of IC_2 are connected to 16 strain gauge based transducers. When the selection lines of both the ICs are enabled, connectivity of any shunt resistor from the resistor bank can be established with any transducer. Both the resistor selection and channel selection circuits are interfaced to an 8051 based micro-controller P89V51RD2 (Philips). The microcontroller is connected to the calibration control computer (CCC) through RS232 interface. The outputs of the transducers are connected to a computer based data acquisition system.

Table 1 summarizes the resistors needed for carrying out multi-point shunt calibration. Theoretical values of the resistors needed for simulating different levels of bridge output are calculated using equation-4 taking bridge resistance R as 350Ω. Nearest values of the available resistors are used. Corresponding values of the simulated bridge outputs are calculated using equation-3.

Table 1: List of resistors needed to simulate different levels of bridge output as a percentage of full scale output.

Resistor No.	Expected Voltage Output (mV)	Output (% FSO)	Calculated Resistance (kΩ)	Nearest available Resistors# (kΩ)	Actual Voltage Output (mV)
NC*	0	0%	NC*	--	0
R1	3	10%	291.491	300	2.91
R2	6	20%	145.658	150	5.82
R3	7.5	25%	116.491	120	7.28
R4	9	30%	97.047	100	8.73
R5	12	40%	72.741	75	11.64
R6	15	50%	58.158	56	15.57
R7	18	60%	48.436	47	18.55
R8	21	70%	41.491	43	20.26
R9	22.5	75%	38.713	39	22.33
R10	24	80%	36.283	36	24.19
R11	27	90%	32.232	33	26.37
R12	30	100%	28.991	30	28.99
*NC-No connection. #Tolerances of Resistors ±1%					

4. FABRICATION: HARDWARE & SOFTWARE

A prototype of the automatic shunt calibration system was fabricated based on the above design. Fig. 5 shows the prototype of the developed ASCS. The Graphical user interfaces (GUI) are shown in figures-6 and 7.

The resistor bank, analog multiplexers and the terminal blocks were integrated and interfaced on a single side printed wiring board as per the circuit diagram of Fig. 4. An 8051 microcontroller development kit (UTS-MC-KIT-M7.1.1, Unistring Technologies) was used to control the selection of transducers and shunt resistors. The enable and address lines of both the multiplexer ICs were interfaced to the microcontroller using a ribbon connector. The kit was interfaced to the calibration control computer using RS-232 interface.

Fig. 5: Prototype of the ASCS. Right side board consists of the resistor bank, analog multiplexer ICs and the terminal blocks for interfacing. The left side board is the 8051 microcontroller based development kit (P89V51RD2).

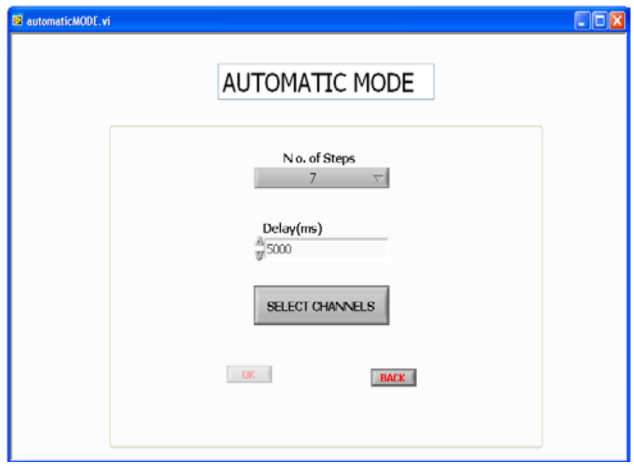

Fig. 6: Graphical user interface for selection of no. of points (steps) 3/5/7/9/11. Intentional delays between successive calibration steps can be assigned.

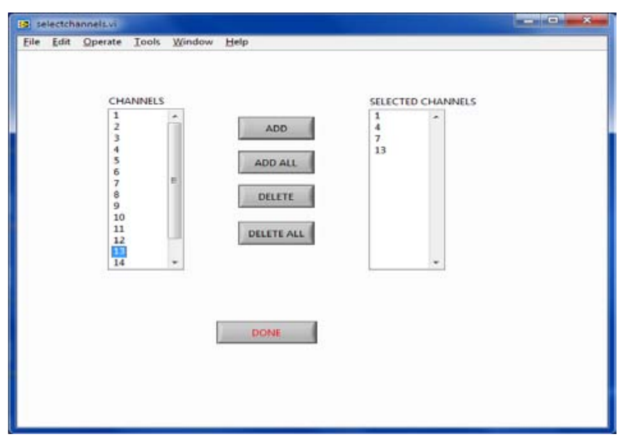

Fig. 7: Graphical user interface for channel selection

The embedded software for transducer selection and shunt resistor selection was developed in Embedded C using μVision-4 IDE. The related tool sets were used for compilation, debugging and dumping the corresponding binary code into the microcontroller. Graphical user interfaces (GUI) for controlling the shunt calibration process like selection of manual/automatic mode, number of points (3/5/7/11), intentional delay and number of channels were developed using LabVIEW software.

5. 5. TEST & ANALYSIS

An integrated test set-up, as shown in Fig. 8, was used for testing and validation of the ASCS. Sixteen Strain gauge based Pressure transducers (Make: Honeywell Sensotec, Model: Z, Range 100 kgf/cm^2, Bridge resistance 350Ω and sensitivity 3mV/V/(kgf/cm^2)) were interfaced to 16 channels of the Automatic Shunt Calibration System.

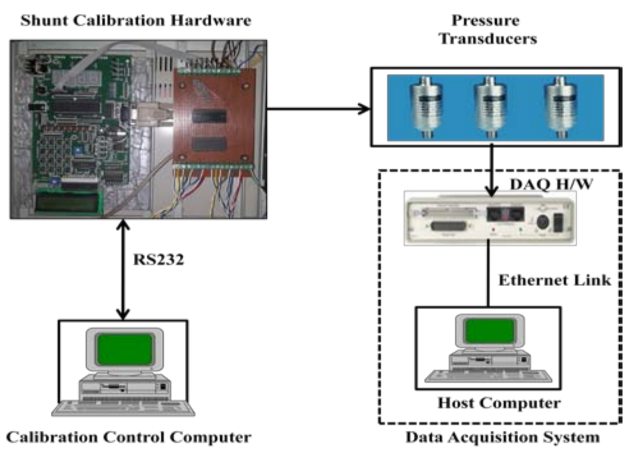

Fig. 8: Integrated test set-up for ASCS to carry out multi-point shunt calibration.

10V DC excitation to each transducer was applied from a regulated DC power supply unit (Make: TDK-Lambda, Model: GEN 30-25 HFP). The required power for the microcontroller board and the multiplexer ICs were given from another regulated DC power supply unit. The outputs of the pressure transducers were connected to 16 input channels of a computer based Data Acquisition System (DAS). The DAS consists of data acquisition hardware (Make: Dataq Instruments, Model: DI-720-EN) connected by Ethernet link to a host computer containing Windaq Pro+ software for configuration and control of data acquisition. After powering on all the sub-systems, the DAS was configured for data acquisition of 16 pressure transducer channels. Initial offsets of each channel were nullified to make the output zero.

Initially multi-point shunt calibration of each channel was carried out in manual mode and the DAS outputs were found to be matching with the expected outputs. This cleared all the channels and gave the confidence to go ahead for automatic multi-point shunt calibration. 3-point, 5-point, 7-point and 11-point shunt calibration of all 16 channels were carried out sequentially and corresponding output data were acquired in the DAS.

Table 2: Results of 3-point, 5-point, 7-point and 11-point shunt calibration. Maximum error is 0.888%.

Cal. Steps/ points	% of FS Output	Resistor No.	Shunt Resistance (kΩ)	Expected Output (mV)	Actual Output (mV)	% Error
3	0%	NC	NC	0.0	0.01	--
	50%	R6	56	15.57	15.69	0.771
	100%	R12	30	28.99	29.18	0.655
5	0%	NC	NC	0.0	0.02	--
	25%	R3	120	7.28	7.31	0.412
	50%	R6	56	15.57	15.69	0.771
	75%	R9	39	22.33	22.45	0.537
	100%	R12	30	28.99	29.17	0.621
7	0%	NC	NC	0.0	0.05	--
	10%	R1	300	2.91	2.92	0.344
	25%	R3	120	7.28	7.31	0.412
	50%	R6	56	15.57	15.68	0.706
	75%	R9	39	22.33	22.45	0.537
	90%	R11	33	26.37	26.60	0.872
	100%	R12	30	28.99	29.19	0.690
11	0%	NC	NC	0.0	0.04	--
	10%	R1	300	2.91	2.93	0.687
	20%	R2	150	5.82	5.83	0.172
	30%	R4	100	8.73	8.80	0.802
	40%	R5	75	11.64	11.68	0.344
	50%	R6	56	15.57	15.69	0.771
	60%	R7	47	18.55	18.71	0.862
	70%	R8	43	20.26	20.44	0.888
	80%	R10	36	24.19	24.22	0.124
	90%	R11	33	26.37	26.60	0.872
	100%	R12	30	28.99	29.19	0.690

Percentage error was calculated for each step of each channel. Maximum error was found to be 0.888% (which was observed at 70% level of 11-point calibration, channel no.6). All the multi-point calibration results of channel-6 along with the errors are presented in Table 2.

6. CONCLUSION

Prototype of an automatic shunt calibration system has been designed and fabricated. Using this system we have successfully carried out 3-point, 5-point, 7-point and 11-point field calibration of up to 16 strain gauge based pressure transducers. Maximum calibration error was found to be

0.888% of full scale output. With this system, the overall field calibration time has been reduced drastically from 10 hours (using manual shunt calibration) to less than 30 minutes for 11-point calibration of 16 pressure transducers making it more suitable for time critical applications. We are working further to reduce the overall calibration time and to optimize the requirements of resources by carrying out the control of shunt calibration and the data acquisition employing suitable feedback mechanism. We are also trying to enhance the accuracy of calibration and extend this concept to calibration of more than 100 channels.

7. ACKNOWLEDGEMENT

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