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MOUNTING METHOD OF STRAIN GAUGES TO MEASURE THREE
DIMENSIONAL LOADS AT TIP OF A HOLLOW CYLINDER

FIELD OF THE INVENTION

5 The present invention relates to method of mounting strain gauge. More particularly, the present invention relates to a method of mounting a plurality of strain gauges on a hollow cylinder for measuring three-dimensional dynamics loads acting on the hollow cylinder in a random manner.

10 BACKGROUND OF THE INVENTION

In structural monitoring testing, there is often a need to measure applied loads on the structures of interests. Various kinds of load cells have been developed for such
15 measuring purposes. However, to measure loads applied on specific structures, specially tailored methods are needed, as the precise positioning of the sensors, mounting method of the sensors, the number of sensors used critically effected an overall performance of the load measurement instrumentation.

20 Strain gauge is one of the sensors used to form various load cells that is suggested to be used for the purpose of the present invention. Its resistance will change, as it is deform together with the bonded to structure, which is stressed. Such strain gauge is developed from an ultra thin heat-treated metallic foil and is chemically bonded to a thin dielectric layer. It is then mounted onto a structure surface with specially formulated
25 adhesives. As a surface to which the strain gauge is attached becomes strained, such stretches or compresses of the structure transferred to the strain gauge and reflects in its resistance change, which is in certain relation to the applied load. Further, one of the applications of the present invention was proven to be successfully in providing all components of the three-dimensional dynamic load with random applied position.

Usually, structural analysis is to deduce stresses or strains (being results) from applied loads (being causes). At liner elasticity, solution could be straightforward, as results can always be obtained by summing up stresses or strains caused by each load component. Conversely, if one is to deduce causes from results, i.e. determinate applied loads from stresses or strains, is could be more sophisticated.

For example of a load measurement, using measured strain values to derive applied loads, the situation is generally complicated by "cross-talk" effect. This involves a method of finding out individual load components from strains which contributed by multiple load components. Therefore, how to instrument a structure to segregate the effects of different loads from the combined results, is the key point of measuring the applied loads.

Typically, applied three-dimensional dynamic loads which needed to be measured are expected to have a magnitude up to a several tens of kilo Newton in a single direction, random in an acting direction and position at the tip zone of a hollow cylinder structure, which was built with various cross section dimensions. For the purpose of the present invention, such load measuring method must satisfy the following requirements: -

- Must cater for different load acting point at the tip zone
- Must be able to overcome the "cross-talk" effect to provide each load components
- Eliminate temperature influences from strain gauge readings

SUMMARY OF INVENTION

It is an aim of the embodiments disclosed herein to provide a method of positioning strain gauges on an object for measuring an applied load acting on it.

According to one aspect there is provided a method of locating a plurality of strain gauges on an inner surface of a hollow body having a first parameter on a first end and a second parameter on a second end, the method operable to measure load applying on the first end of the hollow body comprising the steps of

attaching a plurality of first of strain gauges along a first parameter path; and attaching a plurality of second of strain gauges and at least one third of strain gauge in orthogonal direction of second parameter path.

According to another aspect there is provided a method of locating a plurality of strain gauges on an outer surface of a hollow body having a first parameter on a first end and a second parameter on a second end, the method operable to measure load applying on the first end of the hollow body comprising the steps of, attaching a plurality of first of strain gauges along a first parameter path; and attaching a plurality of second of strain gauges and at least one third of strain gauge in orthogonal direction of second parameter path.

BRIEF DESCRIPTION OF DRAWINGS

Further feature of the present invention will readily be apparent from the following detailed description of a non-limitative example, with reference to the accompanying drawing, in which:-

FIG. 1 is a side view of a hollow cylinder with a broken section presenting a inner structure of the hollow cylinder in accordance with one preferred embodiment of the present invention;

FIG. 2 is a diagram showing vector representation of a force P having a bending moment M, and their orthogonal components on a right-hand coordinate system;

FIG. 3a is a cross section of the hollow cylinder taken along line U-U of FIG. 1;

FIG. 3b is a diagram showing an X-Y plane having vector representation of a bending moment M reflected in the angle α and its orthogonal components of FIG. 3a resulting by a force P;

FIG. 4a is a cross section of the hollow cylinder taken along line L-L of FIG. 1; and

FIG. 4b is a diagram showing an X-Y plane having vector representation of a bending moment M reflected in the angle α and its orthogonal components of FIG. 4a resulting by a force P .

DETAILED DESCRIPTIONS

Where the same reference numeral appears in more than one of the accompanying drawings, it is used to denote the same element.

FIG. 1 illustrates a side view of a hollow cylinder 100 having a first end 108 and a second end 109 according to one embodiment of the present invention. The first end 108 defines a first inner diameter D_s and the second end 109 defines a second inner diameter D_p . A broken portion 101 on the hollow cylinder 100 is provided for inner viewing purpose. The hollow cylinder 100 is provided with a plurality of first strain gauges 110 mounted along the upper circumferential path 112 of an inner surface 102u and a plurality of second strain gauges 111 mounted along an lower circumferential path 114 of the inner surface 102u. The upper and lower circumferential paths 112 and 114 having centers of circle (not shown) in line with a center of circle of the hollow cylinder 100. Preferably, each of the first and second strain gauges 110 and 111 is a single axial strain gauge.

A flange 105 (being the right end of the hollow cylinder 100 of FIG. 1) is a load applying zone having a force 150, denoted as P , operationally stretching and bending the hollow cylinder 100. Such stretching and bending will cause deformation of the hollow cylinder 100 and hence, physical condition of the strain gauges 110 and 111 is changed.

Each of the first or second strain gauges 110 or 111 is typically a stress sensor. It may be connected to a device for measuring force acting on the hollow cylinder 100.

When the device is energized, a voltage across the first or second strain gauge 110 or 111 is detected. For example, if the force 150 acts on the hollow cylinder 100 which the first and second strain gauges 110 and 111 are attached thereon, an elastic deformation to the hollow cylinder 100 occurs. Such elastic deformation changes the resistance of the first or second strain gauge 110 or 111, thereby changing the voltage detected by the device. Based on the voltage variation, an electrical form of the force 150 may be obtained. Method of positioning the first and second strain gauges 110 and 111 will be explained later in details.

It is preferred that the first strain gauges include five strain gauges 110 and the second strain gauges 111 include four strain gauges. One of the first strain gauges 110 is used for eliminating temperature influence. When the force 150 is applied on the hollow cylinder 100 or restraint applied at 108, uneven load distribution occurs within the vicinity of 108 and 109 in the hollow cylinder 100, for which to be eliminated to obtain more accurate results. It is suggested that the lower circumferential path 114 is configured near the flange 105, preferably, a second distance 124, denoted as L_L , of at least one D_p apart from the second end 109. Likewise, the upper circumferential path 112 is located preferably, a first distance 122, denoted as L_S at least one D_s apart from the first end 108. Having said that, it is also preferred that a distance between the upper and lower circumferential path 112 and 114, denoted as $(L_u - L_l)$ to have a maximum allowable distance apart to attain an optimized result of measurement. As such, for example, the upper circumferential path 112 is located at D_s from the first end 108 and the lower circumferential path 114 is located at D_p from the second end 109 to obtain optimized result.

As shown in FIG. 2, a force 150 denoted as P acting on a body may be resolved into three mutually perpendicular force components, P_x , P_y and P_z oriented along respective axes of a 3-dimensional orthogonal coordinate system. Similarly, a bending moment M acting on the body may also be resolved into three mutually perpendicular bending moment components M_x , M_y and M_z lying along the axes of the same coordinate

system. The directions of the components corresponding to the axes of a right-handed coordinate system.

FIG. 3a illustrates a cross sectional view of the hollow cylinder 100 taken along line U-U (also the upper circumferential path 112). Five first strain gauges 110 are attached along the upper circumferential path 112 and orientated in Z direction on the surface 102u. Four of the five first strain gauges 110 circumferentially in 90° apart from each others. The fifth of the first strain gauges 110 (reference 115 hereinafter) may be placed anywhere between any two of the four first strain gauges 110 along the first circumferential path 112 and orientated in circumferential direction.

FIG. 3b illustrates a diagram showing an X-Y plane having vector representation of a bending moment, denoted as M_{ru} reflected in an angle α and its orthogonal components of FIG. 3a resulting by the force 150. Four of the first strain gauges 110 locating 90° apart from each other are configured to detect readings denoting as ϵ_{1u} , ϵ_{2u} , ϵ_{3u} and ϵ_{4u} in respect of direction Z. The fifth of the first strain gauges 115 locating between the any two of the adjacent first strain gauges 110 with an angle θ , is configured to provide reading denoted as ϵ_{ru} , in respect of a first circumferential direction along the first circumferential path 112.

Similarly, FIG. 4a illustrates a cross sectional view of the hollow cylinder 100 taken along line L-L (also the lower circumferential path 114). Four strain gauges 111 are attached along the lower circumferential path 114 on the surface 102L and orientated in Z direction.

FIG. 4b illustrates a diagram showing an X-Y plane having vector representation of a bending moment M_{RL} reflected in the angle α and its orthogonal components of FIG. 4a resulting by the force 150. Four of the second strain gauges 111 locating 90° apart from each others are configured to detect readings denote ϵ_{1b} , ϵ_{2b} , ϵ_{3b} and ϵ_{4b} in respect of direction Z.

With referenced to FIG. 3b and FIG. 4b, the force 150 may be derived via mathematic algorithm. Using the principal of stress or strain, ε representing reading from the strain gauges 110, 111 and 115, can be found using the equations below:

$$\varepsilon_{1,3} = \frac{1}{E} \sigma_{1,3} + \varepsilon_T$$

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where,

- σ is a stress which may derived from strain gauge reading ε ;
- E is a material Young's modules;
- ε_T is the portion of strain gauge reading purely caused by temperature change
- ε_{Tu} is the reading detected from the strain gauge 115

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, and

for the stress acting on the strain gauges at 90° and 270° ,

$$\sigma_{1,3} = \mp \frac{M_x}{I} + \frac{P_z}{A} = \mp \frac{M_r \sin \alpha}{I} R + \frac{P_z}{A},$$

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for the stress acting on the strain gauges at 0° and 180° ,

$$\sigma_{2,4} = \mp \frac{M_y}{I} + \frac{P_z}{A} = \mp \frac{M_r \cos \alpha}{I} R + \frac{P_z}{A},$$

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where,

- ν is a material Posson's ratio
- R is an inner radius of the corresponding circumferential path
- A is a cross section area of a corresponding circumferential path
- I is a moment of inertia
- P_x, P_y and P_z are load components in X, Y and Z directions respectively
- P_r is a radial load component
- M_r is a bending moment
- M_x, M_y are bending moments about X and Y axes respectively
- α is an angle between P_r and P_x axis

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For the first group of strain gauges 110 attached along the upper circumferential path 112, for which corresponding variables denoted with a subscript "u",

$$\varepsilon_{3u} - \varepsilon_{1u} = \frac{2}{E} \frac{M_{ru} \sin \alpha}{I_u} R_u \quad (\text{EQ. 1})$$

, and

$$5 \quad \varepsilon_{4u} - \varepsilon_{2u} = \frac{2}{E} \frac{M_{ru} \cos \alpha}{I_u} R_u \quad (\text{EQ. 2})$$

Dividing (EQ.1) by (EQ.2), the angle, α may be obtained:

$$\tan \alpha = \frac{\varepsilon_{3u} - \varepsilon_{1u}}{\varepsilon_{4u} - \varepsilon_{2u}} \quad (\text{EQ. 3})$$

10 Then, the square of (EQ.1) and (EQ.2) is being summed as shown below,

$$(\varepsilon_{3u} - \varepsilon_{1u})^2 + (\varepsilon_{4u} - \varepsilon_{2u})^2 = \left(\frac{2}{E} \frac{M_{ru}}{I_u} R_u \right)^2 (\sin^2 \alpha + \cos^2 \alpha), \text{ therefore,}$$

$$M_{ru}^2 = ((\varepsilon_{3u} - \varepsilon_{1u})^2 + (\varepsilon_{4u} - \varepsilon_{2u})^2) \left(\frac{E I_u}{2 R_u} \right)^2.$$

Consider direction of M_{ru} has been reflected in angle α , therefore

$$15 \quad M_{ru} = \left(\frac{E I_u}{2 R_u} \right) \sqrt{((\varepsilon_{3u} - \varepsilon_{1u})^2 + (\varepsilon_{4u} - \varepsilon_{2u})^2)} \quad (\text{EQ. 4})$$

For the second group of strain gauges 111 attached along the lower circumferential path 114, for which corresponding variables denoted with a subscript "l",

$$\varepsilon_{3l} - \varepsilon_{1l} = \frac{2}{E} \frac{M_{rl} \sin \alpha}{I_l} R_l \quad (\text{EQ.5})$$

20 , and

$$\varepsilon_{4l} - \varepsilon_{2l} = \frac{2}{E} \frac{M_{rl} \cos \alpha}{I_l} R_l \quad (\text{EQ.6})$$

Dividing (EQ.5) from (EQ.6),

$$\tan \alpha = \frac{\varepsilon_{3l} - \varepsilon_{1l}}{\varepsilon_{4l} - \varepsilon_{2l}} \quad (\text{EQ. 7})$$

Then the square of (EQ.5) and (EQ.6) is being summed,

$$5 \quad (\varepsilon_{3l} - \varepsilon_{1l})^2 + (\varepsilon_{4l} - \varepsilon_{2l})^2 = \left(\frac{2 M_{rl}}{E I_l} R_l \right)^2 (\sin^2 \alpha + \cos^2 \alpha), \text{ therefore,}$$

$$M_{rl}^2 = ((\varepsilon_{3l} - \varepsilon_{1l}) + (\varepsilon_{4l} - \varepsilon_{2l}))^2 \left(\frac{E I_l}{2 R_l} \right)^2$$

Consider direction of M_{rl} has been reflected in angle α , therefore

$$M_{rl} = \left(\frac{E I_l}{2 R_l} \right) \sqrt{((\varepsilon_{3l} - \varepsilon_{1l})^2 + (\varepsilon_{4l} - \varepsilon_{2l})^2)} \quad (\text{EQ. 8})$$

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With reference to FIG. 1, where the force 150, denoted as P may be resolved into two different orthogonal force P_r and P_z ,

$$M_{ru} = P_r (L_u - L_p) + P_z R_p \quad (\text{EQ. 9})$$

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$$M_{rl} = P_r (L_l - L_p) + P_z R_p \quad (\text{EQ. 10})$$

, where L_u and L_l are the lengths measuring from the second end 109 to the upper circumferential path 112 and the lower circumferential path 114 respectively, and L_p is the thickness of the flange 105.

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Subtracting (EQ. 10) from (EQ. 9), radial load component, denoted P_r , may be expressed as:

$$P_r = \frac{M_{ru} - M_{rl}}{L_u - L_l} \quad (\text{EQ. 11})$$

, and P_x and P_y may also be obtained by

$$P_x = P_r \cos \alpha \quad (\text{EQ. 12})$$

$$P_y = P_r \sin \alpha \quad (\text{EQ. 13}).$$

For the ease of calculation, the angle θ , is configured to be for example 45° from X axes. The bending moment of the fifth first group of strain gauge 115 is,

$$\begin{aligned} M_{Tu} &= (M_{ru} \sin 45^\circ + M_{yu} \cos 45^\circ) \\ &= M_{ru} \sin \alpha \frac{\sqrt{2}}{2} + M_{ru} \cos \alpha \frac{\sqrt{2}}{2} \end{aligned}$$

$$\text{and, } M_{Tu} = M_{ru} (\sin \alpha + \cos \alpha) \frac{\sqrt{2}}{2}$$

10 Stress at the fifth strain gauge 115 with respect of the Z direction is: -

$$\begin{aligned} \sigma_{uT} &= -M_{Tu} \frac{R_u}{I_u} + \frac{P_z}{A_u} \\ &= -M_{ru} (\sin \alpha + \cos \alpha) \frac{\sqrt{2}}{2} \frac{R_u}{I_u} + \frac{P_z}{A_u} \end{aligned}$$

, therefore

$$\varepsilon_{Tu} = -\frac{\nu}{E} (\sigma_{Tu}) + \varepsilon_T \quad (\text{EQ.14})$$

$$15 \quad = \frac{\nu}{E} M_{ru} (\sin \alpha + \cos \alpha) \frac{\sqrt{2}}{2} \frac{R_u}{I_u} - \frac{\nu}{E} \frac{P_z}{A_u} + \varepsilon_T$$

Next, summing ε_{1u} , ε_{2u} , ε_{3u} and ε_{4u} ,

$$\frac{(\varepsilon_{1u} + \varepsilon_{2u} + \varepsilon_{3u} + \varepsilon_{4u})}{4} = \frac{P_z}{EA_u} + \varepsilon_T \quad (\text{EQ. 15})$$

, and subtract (EQ. 15) from (EQ. 14), P_z may be obtained as follow:

$$20 \quad P_z = \frac{EA_u}{1+\nu} \left[\frac{\varepsilon_{1u} + \varepsilon_{2u} + \varepsilon_{3u} + \varepsilon_{4u}}{4} - \varepsilon_{Tu} + \frac{\nu}{E} M_{ru} (\sin \alpha + \cos \alpha) \frac{\sqrt{2}}{2} \frac{R_u}{I_u} \right] \quad (\text{EQ. 16})$$

In accordance with an alternative embodiment of the present invention, strain gauges which obtained ε_{2u} and ε_{4u} may be connected together. Then the force in Z direction P_z may be expressed as,

$$P_z = \frac{EA_u}{1+\nu} \left[\frac{\varepsilon_{1u} + \varepsilon_{3u}}{2} - \varepsilon_{Tu} + \frac{\nu}{E} M_{ru} (\sin \alpha + \cos \alpha) \frac{\sqrt{2}}{2} \frac{R_u}{I_u} \right] \quad (\text{EQ. 17})$$

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In accordance with a further alternative embodiment of the present invention, strain gauges which obtained ε_{1u} and ε_{3u} may be connected together. Then the force in Z direction P_z may be expressed as,

$$P_z = \frac{EA_u}{1+\nu} \left[\frac{\varepsilon_{2u} + \varepsilon_{4u}}{2} - \varepsilon_{Tu} + \frac{\nu}{E} M_{ru} (\sin \alpha + \cos \alpha) \frac{\sqrt{2}}{2} \frac{R_u}{I_u} \right] \quad (\text{EQ. 18})$$

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In accordance with another alternative embodiment of the present invention, the hollow cylinder 100 having a plurality of strain gauges mounting on a outer surface 103 of the hollow cylinder for detecting the force 150 acting on the hollow cylinder.

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From the above algebraic expression, P_x , P_y and P_z may be found based on the detected strain readings, ε_{1u} , ε_{2u} , ε_{3u} , ε_{4u} , ε_{1b} , ε_{2b} , ε_{3l} , ε_{4l} and ε_{Tu} . Five test have been conducted to determine accuracy of the methods provided by the present invention. Results of measured loads against the actual applied loads in kilo Newton and percentage of error are presented in TABLE I.

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TABLE I

Test	Applied Loads (kN)			Measured Loads (kN)			Error (%)		
	P_x	P_y	P_z	P_x	P_y	P_z	P_x	P_y	P_z
#1	0	0	61.2	-0.05	-0.38	61.27	-	-	0.11
#2	0	50	0	-0.72	53.86	1.04	-	7.72	-
#3	50	0	0	50.64	-1.73	-1.64	1.28	-	-
#4	0	-50	0	-0.18	-54.12	-1.68	-	8.24	-
#5	-50	0	0	-50.62	1.5	-1.87	1.24	-	-

It is understood by those skilled in the art that even though numerous characteristics and advantages of various preferred embodiments of the present invention have been set forth in the foregoing description, this disclosure is illustrative only. Other modification may be made, especially in matters of structure, arrangement of parts and/or steps within the principles of the invention to the full extent indicated by the broad general meaning of the appended claims without departing from the scope of the invention.

CLAIMS

1. A method of locating a plurality of strain gauges on an inner surface of a hollow
5 body having a first parameter on a first end and a second parameter on a second end, the
method operable to measure randomly applied load applying on the first end of the
hollow body comprising the steps of:
attaching a plurality of first strain gauges along a first parameter path; and
attaching a plurality of second strain gauges and at least one third strain gauge in
10 orthogonal direction of second parameter path.
2. A method of locating a plurality of strain gauges on an outer surface of a hollow
body having a first parameter on a first end and a second parameter on a second end, the
method operable to measure load applying on the first end of the hollow body comprising
15 the steps of:
attaching a plurality of first strain gauges along a first parameter path; and
attaching a plurality of second strain gauges and at least one third strain gauge in
orthogonal direction of second parameter path.
- 20 3. The method of locating a plurality of strain gauges according to claim 1 or 2,
wherein the first parameter path includes four first strain gauges and the second
parameter path includes four second strain gauges and one third group of strain gauges.
4. The method of locating a plurality of strain gauges according to claim 3, wherein
25 the adjacent first strain gauges are configured to be 90° apart from each other relative to a
first corresponding center along the first parameter path and the adjacent second strain
gauges configured to be 90° apart from each other relative to a second corresponding
center along the second parameter path.

5. The method of locating a plurality of strain gauges according to claim 3, wherein the at least one third strain gauge is configured to locate in space between any two adjacent second strain gauges along the second parameter path.

5 6. The method of locating a plurality of strain gauges according to claim 5, wherein the third strain gauges is configured 45° apart from the any two adjacent second strain gauges relative to the second corresponding center.

7. The method of locating a plurality of strain gauges according to claim 1 or 2,
10 further comprising the step of configuring the first strain gauges and the second strain gauges operable to sense an corresponding applied load component in any direction randomly.

8. The method of locating a plurality of strain gauges according to claim 1 or 2,
15 further comprising the steps of:

locating the first parameter path at a first distance having at least one first parameter from the first end; and

locating the second parameter path at a second distance having at least one second parameter from the second end.

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9. The method of locating a plurality of strain gauges according to claim 1 or 2, further comprising the step of configuring the first parameter path and second parameter path to have a maximum allowable distance from each other.

25 10. The method of locating a plurality of strain gauges according to claim 1 or 2, wherein the first parameter path is located nearer to the first end than the second parameter path.

11. The method of locating a plurality of strain gauges according to claim 1 or 2,
30 further comprising the steps of:
obtaining readings from strain gauges; and

calculating three orthogonal components of the randomly applied dynamic load.

12. The method of locating a plurality of strain gauges according to claim 1 or 2, wherein the hollow body is a hollow cylinder having the first end defining a first diameter and the second end defining a second diameter.

13. The method of locating a plurality of strain gauges according to claim 12, wherein three orthogonal components of the randomly applied dynamic load, denoted as P_x , P_y and P_z respectively are expressed as below at any one time:

$$10 \quad P_x = P_r \cos \alpha;$$

$$P_y = P_r \sin \alpha; \text{ and}$$

$$P_z = \frac{EA_u}{1+\nu} \left[\frac{\varepsilon_{1u} + \varepsilon_{2u} + \varepsilon_{3u} + \varepsilon_{4u}}{4} - \varepsilon_{tu} + \frac{\nu}{E} M_{ru} (\sin \alpha + \cos \alpha) \frac{\sqrt{2}}{2} \frac{R_u}{I_u} \right];$$

where;

- ε is the strain gauge reading taken from the respective denoted strain gauge;

$$15 \quad \bullet \quad \sigma \text{ is a stress, for which } \varepsilon = \frac{1}{E} \sigma + \varepsilon_T;$$

- E is a material Young's modules;

- ε_{tu} is the third strain gauge reading purely caused by temperature change;

- ν is a material Posson's ratio;

- R_u is an inner radius of the second circumferential path;

$$20 \quad \bullet \quad A_u \text{ is a cross section area of the second circumferential path;}$$

- I_u is a moment of inertia of the second circumferential path;

- P_r is a radial load component, for which $P_r = \frac{M_{ru} - M_{rl}}{L_u - L_l}$;

- M_{ru} is a bending moment of the radial load at the second circumferential path and M_{rl} is a bending moment of the radial load at the first circumferential path;

$$25 \quad \bullet \quad \alpha \text{ is an angle between } P_r \text{ and } P_x;$$

- L_l and L_u is a length measuring from the second end to the first circumferential path and the second circumferential path respectively.