March 22, 1966 T. M. CURRY 3,241,360

PARALLEL MEMBER MOMENT TRANSFER MEANS

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Fig. 1.

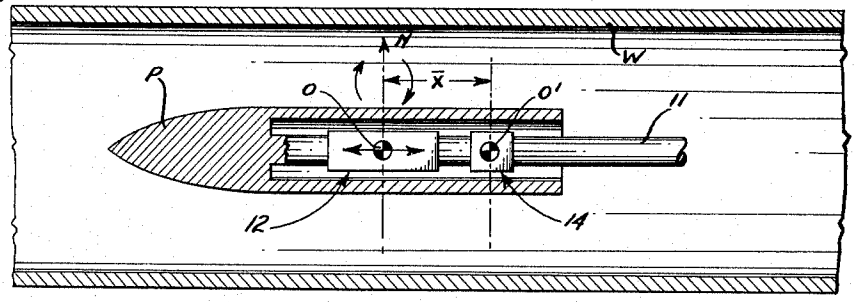


Fig. 2a.

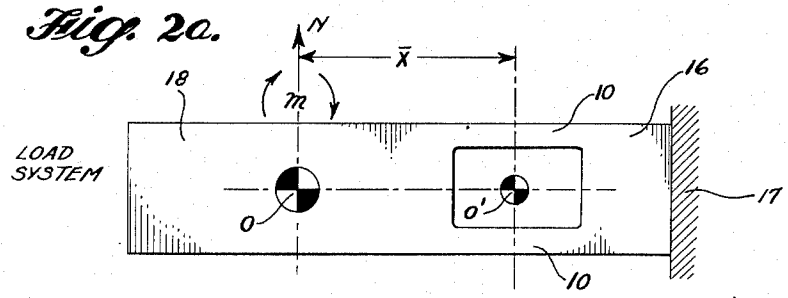


Fig. 2b.

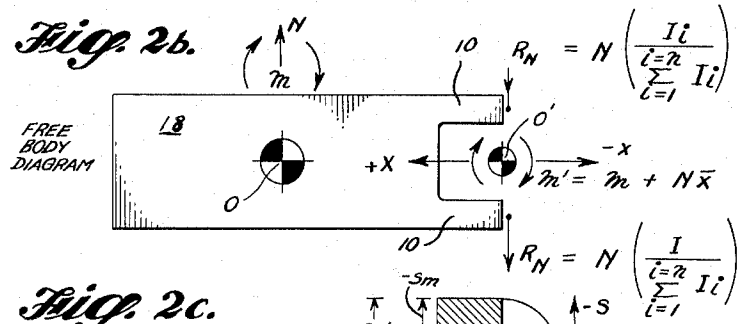


Fig. 2c.

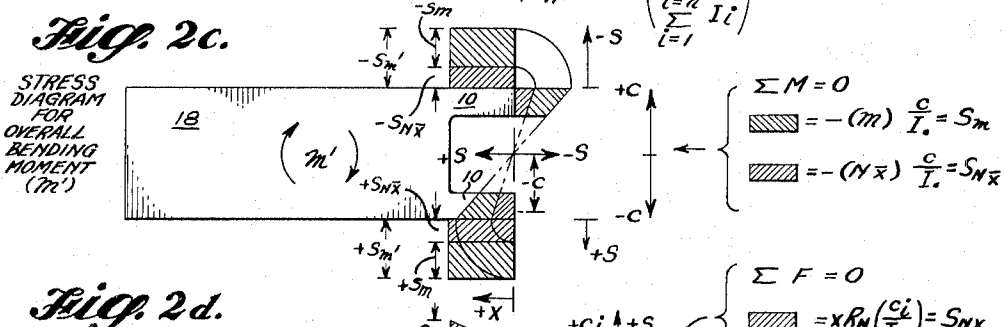
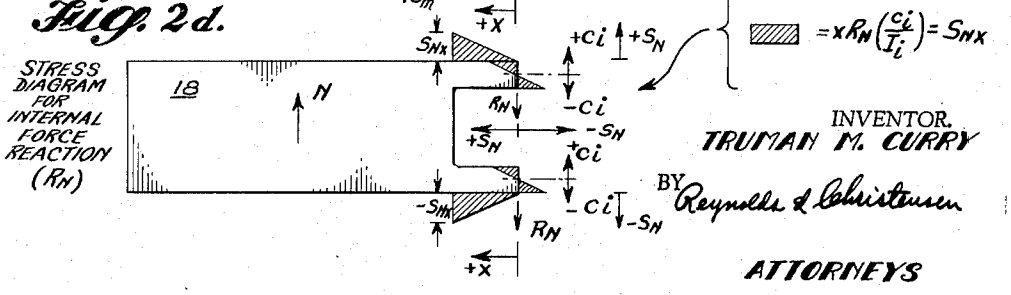


Fig. 2d.



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Fig. 3a.

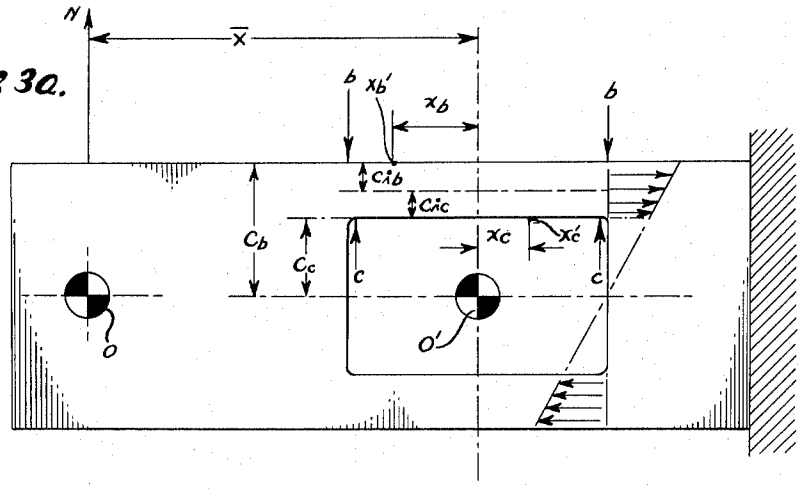


Fig. 3b.

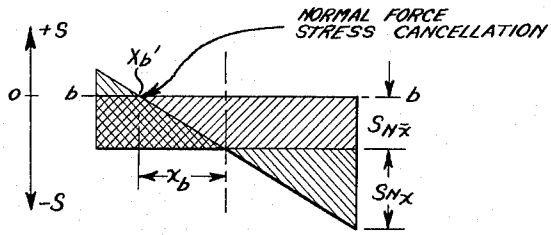


Fig. 3c.

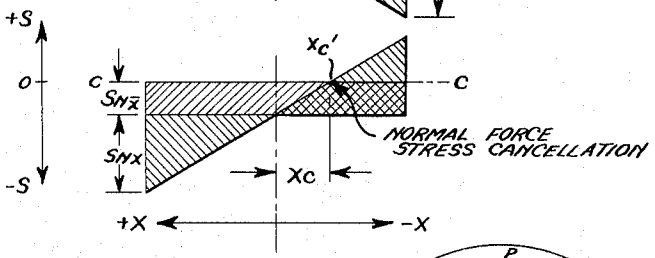


Fig. 5.

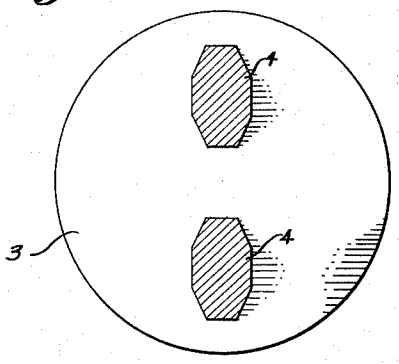
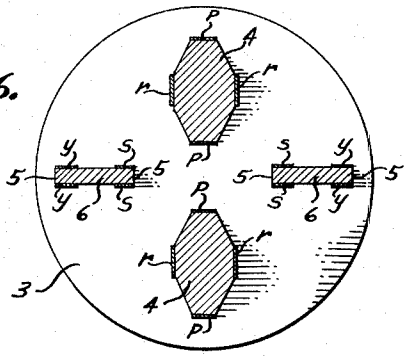


Fig. 6.



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Fig. 4(a)1.

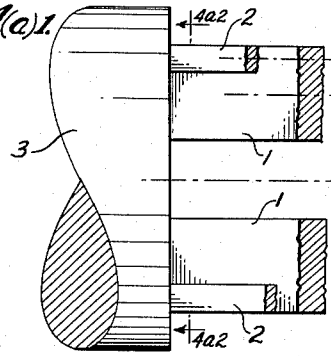


Fig. 4(a)2.

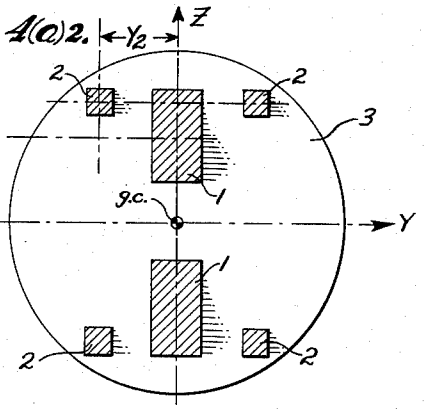


Fig. 4(b)1.

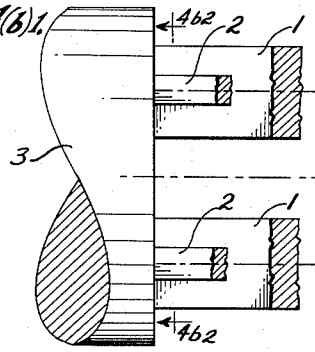


Fig. 4(b)2.

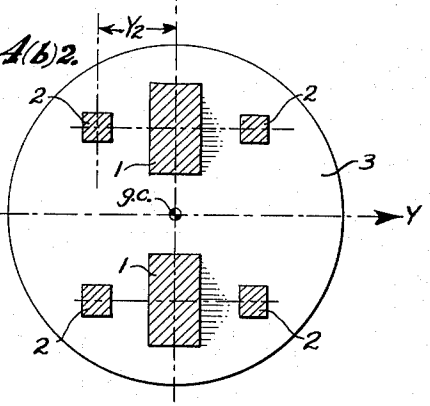


Fig. 4(c)1.

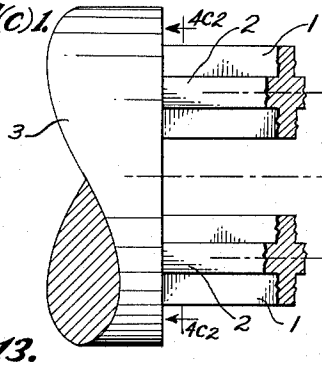


Fig. 4(c)2.

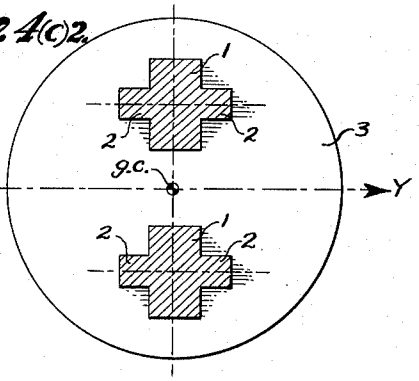
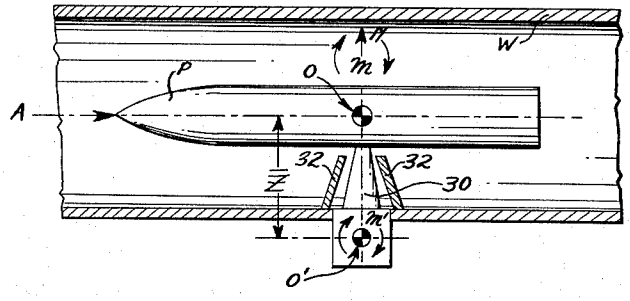


Fig. 13.



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PARALLEL MEMBER MOMENT TRANSFER MEANS

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Fig. 7.

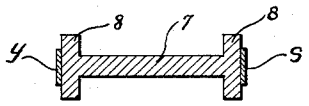


Fig 8.

Fig. 9.

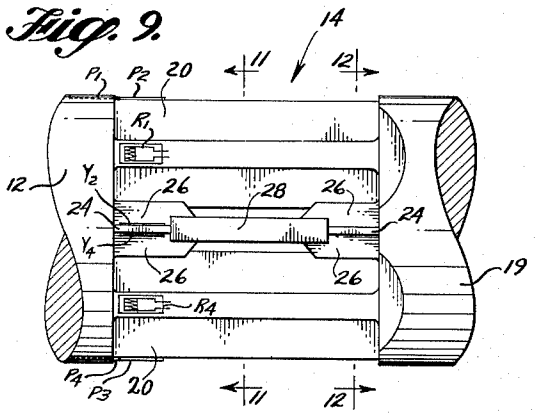


Fig. 11.

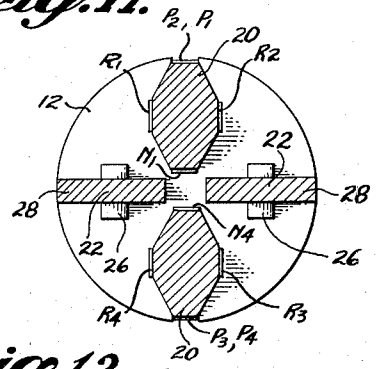


Fig. 10.

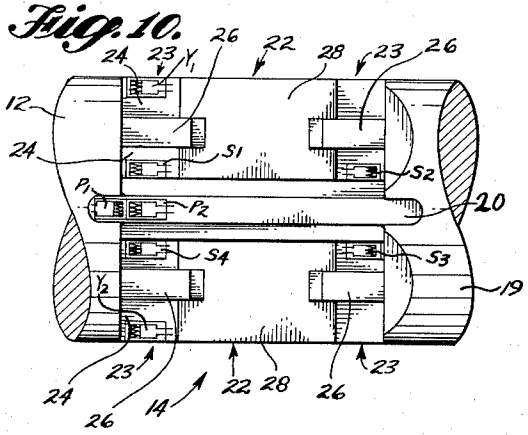
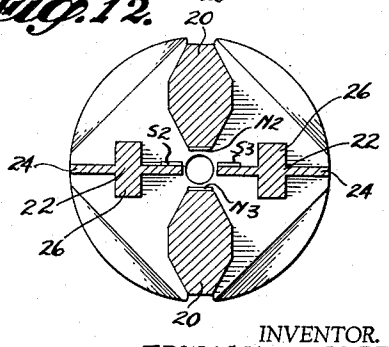


Fig. 12.



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Patented Mar. 22, 1966

3,241,360
PARALLEL MEMBER MOMENT TRANSFER MEANS

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(4802 E. Mercer Way, Mercer Island, Wash.)
Filed May 24, 1965, Ser. No. 463,451
13 Claims. (Cl. 73—147)

This application is a continuation-in-part of my co-pending application Serial No. 154,686, filed November 24, 1961, now abandoned.

This invention relates generally to instruments for measuring forces and moments such as the aerodynamic forces and moments acting on models in wind tunnel testing, and the like. More particularly, it relates to a device for directly measuring moments about a moment center located remote from the measuring device itself. It provides new configurations for a device capable of incorporation into a strain gauge balance for directly measuring at a measuring point moments about a moment center in the balance remote from the measuring point as though the device itself were, in fact, located at the moment center. While the invention is herein illustratively described in terms of presently preferred forms thereof in connection with wind tunnel model testing, it will be recognized that various modifications and changes may be made therein with respect to details and adaptations for different applications without departing from the essential features involved.

Various types of strain gauge balances have been designed to measure aerodynamic forces and moments acting on models in wind tunnel tests and other testing methods, each balance resolving such forces into the usual six components of axial, normal and side force and pitching, yawing and rolling moment. Severe space problems now occur because of the very small size models which must be used in supersonic and hypervelocity wind tunnels. The axial force measuring element is characteristically weakest to bending moments and is therefore frequently located at the point of least bending moment, the moment center. Because it is difficult to design a compact balance with other measuring elements grouped about or superimposed on the axial force measuring element at the moment center, it is often necessary or convenient in designing such small balances to locate the elements for measuring the transverse loads at points remote from the moment center. However, strain gauge pairs measure moments about their own centers and readings taken at such points must be corrected by a system of mathematical or analog computations to read about the true moment center of the balance. All such methods increase the opportunities for human and mechanical errors in obtaining and analyzing the test results. In addition, there are increased loads on the gauges which are located at points of larger bending moment. Thus, in order to maintain given factors of safety, larger measuring elements and gauges must be used, resulting in reduced sensitivity.

Hence in the past designers have had to compromise regarding certain other considerations. For example, axial force element design flexibility has been sacrificed by locating that element external to the moment center where bending moments are greater. In some cases balance sensitivity and instrumentation sensitivity have been sacrificed by locating the transverse load measuring elements external to the moment center, relying upon analog or mathematical computation to determine the transpositional corrections necessary to refer the readings to the moment center. In other cases space utilization has been compromised by designing all the components grouped or superimposed geometrically at the moment center.

Although some of the designs making the above sacrifices have been successful because the conditions were not critical, it is, of course, advantageous even then to avoid such compromises. However, where the space factor is critical, as in today's hypervelocity tunnels utilizing smaller models, another solution is mandatory. The higher loads characteristic of these tunnels are in some cases attainable only for a very short period of time, of the order on one-tenth of a second, for example. Such conditions demand higher sensitivity in the balances used, as well as more compactness. To avoid the necessity of compromising these requirements, the present invention provides improved devices capable of measuring the moments directly about the moment center, eliminating the necessity for transpositional corrections, while locating the applicable measuring elements away from the moment center in order to allow more compactness of design.

The principal object of this invention is to provide improved measuring devices for incorporation into strain gauge balances to accomplish such direct measurements from a remote point mechanically and automatically as though located at the moment center itself, overcoming the above-mentioned difficulties.

This advancement in the art of wind tunnel testing has as a further object to provide improvements in strain gauge balances wherein certain of the measuring elements are located at points remote from the moment center about which measurements are desired while also improving balance sensitivity and instrumentation simplicity.

A related object is to provide greater flexibility of design in balances having transverse load measuring elements located remotely from the axial force measuring element.

A further related and highly important object is to provide improved balance designs whereby compactness can be achieved without a corresponding sacrifice in strength or ability to measure accurately all the desired components of force and moment.

In a narrower sense, an object of this invention is to provide improved strain gauge balances of generally parallel beam configuration capable of measuring the five transverse load components, the structure inherently measuring side force, normal force and rolling moment while measuring directly the pitching and yawing moments about a selected moment center remote from the geometric center between cooperating moment gauges.

A further object is to provide improved strain gauge balance designs which, while achieving the above objects and purposes, will minimize the interactive stress levels among the various load components.

Another object of this strain gauge instrument improvement is to provide, through the utilization of a parallel beam moment transfer cage, improved design criteria whereby given load and sensitivity requirements may be matched. That is, it is an object of this invention to provide an improved design technique for easily controlling the relative sizes of beams for a working balance configuration.

An additional object is to provide certain improved beam shapes and combinations of parallel beam structures useful in stain gauge balances and other force measuring instruments.

In accordance with this invention transverse moments acting on a balance about a certain moment center are measured directly (i.e., independently of the effects of transverse forces acting on the balance) by means including a moment transfer cage and associated strain gauges offset physically from that center. In the case of a strain gauge balance used for wind tunnel model testing, both pitching moment and yawing moment may be measured directly in this manner without necessity for grouping the associated balance components about

the moment center of the test model. Equally important, direct readings or indications of these two moments may be obtained without necessity for compunting correction factors necessary to account for the effects of transverse forces, i.e., normal force and side force, acting at or resolved to the moment center.

In achieving these results this invention provides a novel moment transfer cage structure and physical location of strain gauges on beam elements therein within the essentially critical relationship necessary for moment transfer. Accordingly, each strain gauge which is to sense a strain component due to a transverse moment is located at a mathematically predetermined point along a beam element at which the contributions of stress from transverse forces applied at or resolved to the remote moment center cancel out. Thus, a pair of strain gauges so mounted on opposing measurement surfaces in the measurement plane are enabled cooperatively to sense the true moment about the remote moment center independently of stresses in the balance due to such transverse force. The moment transfer cage designs disclosed herein are devised to take best advantage of these principles while also meeting other design criteria.

The invention resides more specifically in preferred structural embodiments of the moment transfer cage and associated strain gauges, particularly in certain stabilized beam structures used therein. Within the mathematical limitations of the principle of stress cancellation involved and other requirements imposed, the particular configurations and transverse locations of the measuring beams in the moment transfer cage designs shown herein minimize the interactions between the various components of force and moment.

These and other features, objects and advantages of this invention will become more apparent from the following detailed description and development of the principles involved, taken in connection with the accompanying drawings which illustrate the principles involved and certain presently preferred forms thereof.

FIGURE 1 is a somewhat diagrammatical sectional side view of a model mounted within a wind tunnel in the usual manner on a cantilever balance of the preferred type for incorporation of the invention.

FIGURES 2(*a*) through 2(*d*) constitute a series of diagrams to aid in demonstrating the principle of stress cancellation in a simple two-beam structure. FIGURE 2(*a*) is a diagram of the two-beam load system, FIGURE 2(*b*) is a free body diagram indicating the reactions at the center line of the two-beam system, FIGURE 2(*c*) is a stress diagram showing the overall bending moment stresses due to moments at the center of the beam system, and FIGURE 2(*d*) is a diagram showing stresses due to shear forces at the center of the beam system.

FIGURES 3(*a*) through 3(*c*) are stress diagrams of the same two-beam system as further aids in the development of the stress cancellation principle. FIGURE 3(*a*) shows the complete two-beam system as in FIGURE 2(*a*) on a larger scale and FIGURES 3(*b*) and 3(*c*) show the normal force stresses acting at the surfaces *b*—*b* and *c*—*c*, respectively, of FIGURE 3(*a*).

FIGURE 4(*a*)1 is a fragmentary side view and FIGURE 4(*a*)2 is a sectional view taken on line 4*a*2—4*a*2 in FIGURE 4(*a*)1, showing one moment absorbing stabilizer structure useful in the improved balance. FIGURES 4(*b*)1, 4(*b*)2, 4(*c*)1 and 4(*c*)2 are similar sets of views showing alternative stabilizers.

FIGURE 5 is a transverse sectional view of a two-beam system utilizing a beam of octagonal cross section.

FIGURE 6 is a transverse sectional view of a four-beam balance system utilizing octagonal beams in the vertical plane and rectangular beams in the horizontal plane, showing strain gauges mounted on selected surfaces of the beams.

FIGURE 7 is an enlarged transverse sectional view of an I-beam which may be incorporated in the balance, having strain gauges mounted on the outer flange surfaces thereof.

FIGURE 8 is a perspective view of a strain gauge balance incorporating a moment transfer cage designed according to this invention in conjunction with a typical axial force measuring section, showing strain gauge positions thereon.

FIGURES 9 and 10 are side and top views, respectively, of the moment transfer cage portion of the balance illustrated in FIGURE 8.

FIGURE 11 is a transverse sectional view taken on line 11—11 of FIGURE 9.

FIGURE 12 is a transverse sectional view taken on line 12—12 of FIGURE 9.

FIGURE 13 is a somewhat diagrammatical side view of a strut type of mounting incorporating principles of the invention, illustrative of an alternative type of force measuring instrument in which the invention may be incorporated.

Referring to the drawings, in FIGURE 1 a test model P is mounted in wind tunnel W on cantilever sting **11** which is suitably supported on struts or vanes (not shown). Within the model P, the sting or balance comprises an axial force measuring device **12** normally located at the center of gravity (i.e., true moment center) O of the model, and at longitudinal spacing therefrom, a transverse load measuring device **14** employing a moment transfer cage to be described. As will be discussed later, these two measuring devices preferably constitute integral parts of a one-piece balance structure. Because of normally greater transverse size and less strength in a balance structure having transverse load measuring elements grouped about the axial force measuring element, the former are frequently located at a point O′ spaced longitudinally from the moment center by the distance $\bar{x}$ as shown in FIGURE 1. That expedient is not new with this invention. Further, since pairs of strain gauges measure moments directly about their own moment centers, the gauges in measuring device **14** measure moments about the point O′. Therefore in conventional balances of this type moments sensed by strain gauges in the measuring device **14** must be corrected mathematically in order to refer the measurements to the moment center O. These transference corrections are made by use of the following equations:

$$m=m'-N\bar{x} \quad (1)$$

$$n=n'-S\bar{x} \quad (2)$$

where m is the pitching moment about the desired center O, m' is the pitching moment actually sensed by the gauges, i.e., the moment about the measuring gauge center O′, N is the normal force, S is the side force, n is the yawing moment about O, n' is the yawing moment about O′, and $\bar{x}$ is the distance between the centers O and O′.

In the past it has been necessary to know the actual values of transverse force (normal and side forces) to make the above-mentioned mathematical transfer or to know values of electrical signals proportional to these forces if corrected moment values are to be determined with analog apparatus. The result has been great opportunity for mechanical or human error. In addition, conventional design of these balances has resulted in unduly massive and bulky structures and in unduly high loads on the strain gauges. As an incidental result, instrument sensitivity has been sacrificed.

Consequently, the stress cancellation theory was developed in the art in order to overcome these and related shortcomings of previous balance construction techniques. For illustration the stress cancellation theory involved is developed with respect to a simple two-beam system.

Such a two-beam system is shown in FIGURE 2(*a*) wherein beams **10** constitute the measuring system and can be considered as normal force and pitching moment beams of a strain gauge balance. The cantilever structure is supported by the base portion **16** mounted at

ground symbol **17**. The remainder of the cantilever structure is represented by the numeral **18**, and point O represents the moment center about which measurements are desired. The centroid O′ of the beam system is displaced longitudinally from moment center O by the axial distance $\bar{x}$, for any of several possible reasons already discussed. The arrow labeled N represents the normal force applied on the model resolved to the moment center, and the moment m is the resolved moment in the pitching moment plane at the moment center.

In FIGURE 2(b), which is a free body diagram of the outer portion of the system beyond its centroid O′, m' is the overall bending moment about the system centroid O′ caused by normal force N and moment m applied at moment center O. This overall bending moment m' produces an overall bending stress given by the formula

$$S_{m'}=-m'\frac{c}{I_o} \tag{3}$$

where c is the distance from the group centroid to the fiber in question, I_o is the overall group section moment of inertia about its own centroid O′, m' is the pitching moment about O′, and $S_{m'}$ is the overall bending stress due to the moment about O′. By transposing Equation 1 and substituting into Equation 3, the stress becomes

$$S_{m'}=-(m+N\bar{x})\frac{c}{I_o}=-m\frac{c}{I_o}-N\bar{x}\frac{c}{I_o} \tag{4}$$

FIGURE 2(c) is a diagram (satisfying the equation $\Sigma M=O$) showing stresses due only to the overall bending moment m'. It is evident that the overall moment stress distribution along the outside surfaces of individual beams **10** is a constant. (Stresses on the inside surfaces of the two beams are not shown.)

FIGURE 2(d) is a diagram (satisfying the equation $\Sigma F=O$) of stresses due only to the normal force reaction R_N. Tensile stresses in these diagrams are taken as positive. Stresses S_N along the top and bottom outer beam surfaces caused by R_N are there shown to be proportional to the distance x from the center O′ of the beam system. This stress S_N due to normal force N on the system is given by

$$S_N=xR_N\frac{c_i}{I_i} \tag{5}$$

where c_i is the distance from the centroid of each individual beam to the individual fiber thereof in question, and I_i is the individual beam moment of inertia about its own centroid. The reaction R_N in each beam due to normal force is a function of normal force N and the moments of inertia I_i of the individual beams, given as follows:

$$R_N=N\left(\frac{I_i}{\sum_{i=1}^{i=n}I_i}\right) \tag{6}$$

By substitution of (6) into (5) it is seen that stress S_N due to normal force is a function of that force, the axial distance from the center O′ to the point at which stress is being determined, and the individual beam parameters c_i and I_i, as follows:

$$S_N=xN\left(\frac{c_i}{\sum_{i=1}^{i=n}I_i}\right) \tag{7}$$

By superposition of stress $S_{m'}$ due to the overall bending moment m', Equation 4, and stress S_N due to the normal force, Equation 7, the total stress S_T is obtained as follows:

$$S_T=S_{m'}+S_N=-m\frac{c}{I_o}+N\left(\frac{xc_i}{\sum_{i=1}^{i=n}I_i}-\bar{x}\frac{c}{I_o}\right) \tag{8}$$

The total stress at any point x along the beams, therefore, is a function of the moment about the moment center O and the normal force, except when the value of the expression in parentheses on the right-hand side of the equation is zero. By equating this parenthetical expression to zero, it is seen that the condition for cancellation of stresses due to normal force may also be expressed as follows:

$$x\left(\frac{c_i}{\sum_{i=1}^{i=n}I_i}\right)=\bar{x}\frac{c}{I_o} \tag{9}$$

It will be recognized that this equation expresses the condition for cancellation of stresses due to any transverse force resolved to the moment center, that is, it is not limited to the normal force and pitching moment plane. Thus, at points x along the surfaces of the beams where this expression is satisfied, the total stress S_T is due only to the desired moment m resolved to the moment center O in any desired measuring plane. This is evident from Equation 8, which becomes

$$S_T=-m\frac{c}{I_o} \tag{10}$$

In FIGURE 3(a) the two-beam system is shown in enlarged form to illustrate more specifically how the stress cancellation points x are located on the surfaces of an individual beam. A general expression for the point x of stress cancellation for any beam system is obtained by solving Equation 9 for x:

$$x=\bar{x}\left(\frac{c}{c_i}\right)\left(\frac{\sum_{i=1}^{i=n}I_i}{I_o}\right) \tag{11}$$

All factors on the right-hand side of this expression are known for a particular surface in a given configuration of beam system. Thus, the stress cancellation point $x_{b'}$ on the surface b—b of the two-beam system of FIGURE 3(a) is found by solving Equation 11 for the distance x (in this case x_b) from the beam system centroid O′ to that point. The proper values of c and I, this is, numerical values of c_{ib}, c_b, I_i and I_o, are substituted to find x_b. Similarly, the stress cancellation point $x_{c'}$ on the opposite surface c—c of the same beam is found from Equation 11 by substituting the proper values of c_{ic}, c_c, I_i and I_o.

Location of these points $x_{b'}$ and $x_{c'}$ is illustrated in another way in FIGURES 3(b) and 3(c). In connection with FIGURE 2(c) it was shown that the stress $S_{N\bar{x}}$ along the beam surfaces due to the normal force N, when resolved as a moment to O′, is a constant. Taking tensile stress as positive as before, this stress $S_{N\bar{x}}$ along the surface b—b is negative and thus plotted below the line in the stress diagram of FIGURE 3(b). Likewise, the stress $S_{N\bar{x}}$ on the opposite surface c—c is plotted negatively in FIGURE 3(c). Added to this stress in each diagram is the double cantilever stress pattern of $S_{N\bar{x}}$ due to the internal force reaction R_N, as shown in connection with FIGURE 2(d). Distances x_b and x_c are thus obtained from the stress diagrams 3(b) and 3(c) for the respective surfaces. These diagrams illustrate clearly that the desired points are located where the two stresses $S_{N\bar{x}}$ and $S_{N\bar{x}}$ cancel each other out. The only stress still having a value at these points is that due to the moment m about the remote moment center O. This stress S_m (not shown in FIGURES 3(b) or 3(c)) is that given by Equation 10 and shown in FIGURE 2(c) to be a constant along the surfaces of the beams. Strain gauges thus centered on the surfaces at points $x_{b'}$ and $x_{c'}$, respectively, sense only moments m about the moment center O.

Thus in accordance with the known stress cancellation principle different possible configurations of beam systems can be selected whereby Equation 9 is satisfied for pre-

determined stations x lying within the half-length of its beams. Strain gauges which are then located at these stations x along the beam surfaces remain unaffected by the portion of the stress level which is proportional to normal force N (Equation 8), since this stress level is zero at these points. The strain gauges so located are therefore free to measure moments m about the moment center O. An instrument so constructed measures without correction the moments about a point O, though the measuring strain gauges are displaced from that point by the distance $\bar{x}$.

Not every possible balance configuration can be made to satisfy Equation 9 because in many the stress level caused by

$$\bar{x}\frac{c}{I_o}$$

would be too large with respect to that caused by:

$$x\left(\frac{c_i}{\sum_{i=1}^{i=n} I_i}\right)$$

The necessary strength and stress level requirements for accurate measurement could not be provided by such a balance. Therefore, according to the teachings of this invention certain additional criteria are observed in order to successfully apply the principle of stress cancellation as previously described. FIGURES 4(*a*)1 and 4(*a*)2 through 4(*c*)1 and 4(*c*)2 illustrate the considerations involved.

In FIGURES 4(*a*)1 and 4(*a*)2 a practical load measuring cage structure is shown which includes a two-beam system such as that previously discussed. The numeral **3** designates the adjacent structure of the force measuring instrument into which the cage is incorporated. If the instrument is a strain gauge balance, for example, beams **1** may be considered the normal force and pitching moment beams. In addition to the two beams **1** as such, the structure also includes, according to this invention, four moment-absorbing stabilizers **2**, comprising beams of smaller cross section parallel thereto and transversely spaced as great a distance Y_2 from the group centroid *g.c.* as is practical, in this case having their outwardly facing surfaces flush with those of beams **2**. The purpose of beams **2** is to provide a practical means of establishing design control over the relative values of I_o and

$$\sum_{i=1}^{i=n} I_i$$

in Equation 9. By controlling these two factors, greater design flexibility is permitted in that the main beams **1** may now be readily designed to perform the double function of measuring load components in addition to pitching moment and normal force.

The contribution of beams **2** to the overall moment of inertia I_o is shown as follows, for the case illustrated in FIGURE 4(*a*):

$$I_o=4(I_2+A_2Z_2^2)+2(I_1+A_1Z_1^2) \qquad (12)$$

where I_1 and I_2 are the individual moments of inertia of beams **1** and **2** respectively, about the group centroid *g.c.*, A_1 and A_2 are their individual cross sectional areas, and Z_1 and Z_2 are their respective vertical distances from the group centroid *g.c.* The contribution of beams **2** to

$$\sum_{i=1}^{i=n} I_i$$

is:

$$\sum_{i=1}^{i=n} I_i=2I_{i1}+4I_{i2} \qquad (13)$$

where I_{i1} and I_{i2} are the individual moments of inertia of beams **1** and **2**, respectively, about their own centroids.

This configuration provides a means of controlling the relative values of I_o and

$$\sum_{i=1}^{i=n} I_i$$

because I_o may be varied virtually independently of

$$\sum_{i=1}^{i=n} I_i$$

This is shown by considering the respective moments of inertia of beams **2** negligible with respect to those of beams **1**, which justified because of the relatively small size of beams **2**. Hence,

$$I_o\approx 4A_2Z_2^2+2I_1+2A_1Z_1^2 \qquad (14)$$

and

$$\sum_{i=1}^{i=n} I_i\approx 2I_1 \qquad (15)$$

Thus from Equations 14 and 15 L_o may be readily varied nearly independently of

$$\sum_{i=1}^{i=n} I_i$$

by selecting various values of A_2 and Z_2. By keeping Z_2 as large as possible, A_2, and thus I_2, are minimized, thereby enhancing the separation and control over the relative sizes of I_o and

$$\sum_{i=1}^{i=n} I_i$$

An alternative structure is provided by decreasing Z_2 to equal Z_1 as shown in FIGURE 4(*b*). This permits the same stress cancellation pattern in beams **2** as in beams **1**, provided the value of A_2 is properly increased so that Equation 9 is satisfied for the same value of x.

Still another alternative, representing a further step in the progressive refinement in design of the measuring cage, is shown in FIGURE 4(*c*). There beams **1** and **2** are abutted at a common value of Z. The stress cancellation pattern is undisturbed, with respect to pitching moment, so that this configuration is fully equivalent in basic function to that shown in FIGURE 4(*b*), with respect to normal force and pitching moment. But greater structural stability is obtained by integrally joining the principal measuring beams **1** with stabilizing beams **2**, since the latter are of relatively small cross section and might have critical column slenderness ratios if unsupported. While the cruciform section of FIGURE 4(*c*) is much more stable, it may be thought of mathematically as merely a combination of beams **1** and **2**.

An important realization is that since Equation 9 specifies nothing with regard to shape, the moment transfer cage may be designed to meet particular test requirements with any number of parallel beams and with shapes and capabilities meeting the other design criteria previously discussed, so long as the moments of inertia satisfy Equation 9. Instead of the simple rectangular beams in the two-beam system earlier described, it is desirable for certain purposes to utilize a generally elliptical beam cross section which for practical purposes is approximated by the oblate octagonal form such as beams **4** shown in FIGURE 5. This cross section prevents the maximum bending stresses from combining directly at the measuring surfaces as they do in the corners formed by adjacent faces of beams having rectangular cross sections. With this form c_i and I_i will be larger for the

same cross sectional area, but an octagonal form may be chosen for which c_i/I_i is the same as for the rectangular cross section. The result is less interaction between stresses due to the different components of force and moment.

The oblate octagonal cross section may in turn be combined with other parallel members of the same or different shapes. For example, FIGURE 6 shows octagonal beams **4** in combination with two laterally disposed rectangular beams **6** designed limber in response to normal force and pitching and rolling moments, but stiff to side force and yawing moment. Typical strain gauge locations are shown on this configuration. The yawing moment gauges Y and side force gauges S are mounted on the upper and lower surfaces of beams **2** in this case because the edges **5** of these beams are too narrow to accommodate the width of a gauge. When greater strain sensitivity in the yawing moment plane is desired, an I-beam configuration **7** such as that shown in FIGURE 7 is used to replace the beams **6** in FIGURE 6. In such a case an I-beam is chosen having flanges **8** formed with faces broad enough to accommodate the yawing moment and side force gauges, as shown. Fewer gauges and less wiring are necessary with this arrangement. With the I-beam configuration greater values of I_i with respect to I_o may be achieved in the yawing moment plane, thereby facilitating design flexibility. In addition, such beams offer greater stability and higher natural frequency than rectangular beams of the same cross-sectional area.

The different beam configurations and combinations thereof incorporated into a moment transfer cage designed according to this invention and within the limits defined by Equation 9 depend to some extent on the requirements of the instant test or series of tests to be run, such as the size and characteristics of the model to be tested, the nature and accuracy of the data sought, the capabilities of the wind tunnel to be used, and other test conditions and requirements. If forces and moments in one plane only are desired, for example, the designed configuration will be much different from that chosen for a balance which will measure five components of force and moment.

The strain gauge balance shown in FIGURE 8 illustrates a preferred form of this invention designed to measure five components of force and moment. In this case the parallel member moment transfer cage **14** is incorporated into a strain gauge balance in conjunction with a suitable axial force measuring element **12**, such as that disclosed in my earlier filed application, Serial No. 789,059, filed January 26, 1959, now U.S. Patent 3,019,643. This element **12** is located with its center coincident with the moment center of the balance. The moment transfer cage **14** is centered to the rear of the moment center of the balance by the distance $\bar{x}$ (not indicated). The balance thus comprises the supporting base portion **19**, the model supporting tip portion **21**, and an instrument portion interconnecting the base and tip consisting of axial force measuring element **12** and the moment transfer cage **14**. The cantilever rod-like balance, including the moment transfer cage **14** of the present invention is preferably manufactured from one piece of stock. Electric spark discharge milling machines are now used in the construction of such balances of complex configurations which would otherwise be virtually impossible. The one-piece construction is preferable in that it reduces or eliminates unpredictable errors due to creep and failure of soldered or brazed joints caused by temperature effects and due to mechanical hysteresis in such joints. In balances which utilize this invention a rigid construction is particularly important to maintain the moment transfer cage rigid with respect to the remote-moment center about which measurements are desired.

In the particular strain gauge balance illustrated in FIGURES 8 to 12, the parallel member moment transfer cage **14** is designed according to the stress cancellation equation previously developed and utilizes four parallel beams. Beams **20** in the pitching moment plane are of uniform octagonal cross section throughout their length and have vertical and horizontal surfaces just broad enough to accommodate strain gauges. The beams **20** are aligned vertically with the axial center line of the balance and are spaced apart at the center of the balance as shown. These beams are designed having relatively great depth to carry most of the weight of the model and the forces acting thereon in a vertical plane. They are stiff to normal force, pitching moment and rolling moment and have strain gauges mounted thereon as illustrated which are wired in bridge circuit arrangements (not shown) in the usual manner well known in the art to measure those forces and moments.

The yawing moment and side force beams **22** are of somewhat more complicated construction. They are laterally disposed, spaced from each other at the center of the balance symmetrically about the axial center line thereof, and have a varying cross-sectional configuration along their length. These side beams **22** have opposite end portions **23** of cruciform cross section, which are interconnected by force and moment transmitting portions **28** of relatively flat rectangular cross section thin in their vertical dimension. The combination of cruciform portions **23** and retangular portions **28** provides the necessary versatility for moment transfer design according to the invention, permitting more precise fixing of the relationship between shear and bending stresses due to side force, in this case.

As previously shown in the development of the cruciform section of FIGURES 4(*c*)1 and 4(*c*)2, the cruciform portions **23** of these beams may be considered a combination of three beams, a relatively thin horizontally disposed beam of rectangular cross section, and two additional beams on opposite sides vertically thereof of approximately square cross section. The advantage of this configuration is the independent control obtained in the design over stiffness to different kinds of bending. Since side force causes double cantilever bending in each of the side beams, the thicker bar portion **26** of the cruciform portion **23** is located at the side force neutral axis of each beam and thus absorbs little of that force. The web portions **24** of the cruciform therefore support and measure the side force more accurately than would a rectangular cross section of the same moment of inertia about the individual beam axis. On the other hand, a side beam is needed which is strong enough to support the yawing moment load. Stabilizing bar portions **26** of the cruciform sections carry part of this load, but are combined with web portions **24** for stability according to the cruciform section theory previously explained. Though most of the yawing moment load is supported by central bar portions **26**, the point of side force stress cancellation for measurement of maximum yawing moment stress in each side beam is located along the outside edge of the cruciform web portion **24**, so that yawing moment gauges Y may be located there to measure that moment as shown.

The interconnecting web **28** of rectangular cross section constituting the central portion of the side beams is designed to increase the resistance of these beams to slender column failure by stabilizing them without modifying their properties at the section where gauges are mounted. The stress cancellation criteria of the beams are left undisturbed by this variation. The vertical bar portions **26** overlap the central transmitting portions **28** enough to impart substantially uniform stability to the region of transition between the cruciform portion **23** and the rectangular cross-sectional portion **28**.

Another reason for the central rectangular interconnecting portion **28** in the side beams, as distinguished from a uniform cruciform cross section throughout their length, is that the rectangular cross section has a small moment of inertia with respect to normal force, rolling moment

and pitching moment, which are to be supported and measured by beams **20**. This arrangement stiffens the side beams to side force, and to a lesser degree to yawing moment, with respect to the relative stiffness of the normal force beams to these loads. Moment transfer is thereby facilitated, measurable stress levels increased and separation of stresses further enhanced.

Connection of the various pairs of gauges in bridge circuit combinations in the usual manner, such as in my earlier filed application Serial No. 789,059, filed January 26, 1959, now U.S. Patent No. 3,019,643, yields output readings or measurements selective of particular strain gauge signal components while others are eliminated through mutual cancellation in the circuits.

According to this invention the pitching moment and yawing moment gauges on beams **20** and beams **22**, respectively, are placed as shown at points of normal and side force stress cancellation in order to measure these moments directly about the remote moment center located forward of the moment transfer cage itself. These points are determined mathematically for the particular configuration according to the criteria herein described.

While the above-described particular configuration has proved to be of maximum accuracy and efficiency in achieving results desired for certain test conditions, it is to be recognized that other configurations are or may be utilized for other testing conditions and requirements without departing from the essential features involved in this invention.

A parallel member moment transfer cage designed according to this invention is applicable, not only to the upstream cantilever mounting of normal wind tunnel testing, but also to other testing modes. As one particular example, FIGURE 13 shows a model P mounted within a wind tunnel W upon a supporting strut **30**. The strut-protecting shield **32** is cut away to reveal the strut **30**. A strain gauge balance designed for measurements in such a mounting takes on a somewhat different configuration adapted to the situation, but may still utilize the principles of the present invention. Thus, an element for measuring axial force A on the model may be mounted at point O within the model. Then according to this invention a parallel member moment transfer cage may be mounted at a point O′ external to the tunnel and aligned transversely of the model with the moment center O and separated therefrom by the distance $\bar{z}$ as shown. The strut **30** must necessarily be constructed to transmit all the components of force and moment acting on the model P to the moment transfer cage at O′. Measurement of moments m' taken at O′ are then automatically transferred by such a moment transfer cage to the moment center O as though the cage itself were located at that point.

It will also be recognized by those skilled in the art that the present invention has many other force measuring applications as well, not necessarily related to wind tunnel model testing, such as for measuring strain in engine test stands and aircraft control stick force transducers to name two specific examples. Thus, it will be understood that various modifications with regard to details of configuration and application are possible within the spirit and scope of this invention, and that those herein illustrated and described are not to be taken as restrictive in nature.

I claim as my invention:

1. A device for measuring moments, with relation to a predetermined moment center therein, comprising an elongated body subject both to a moment acting in a longitudinal plane of said body and to a transverse force simultaneously applied thereto in said plane, said body including an elongated beam structure spaced longitudinally from said moment center, said beam structure comprising a pair of parallel beams spaced apart transversely of the body in said plane and at least two pairs of stabilizer beam portions, one pair operatively associated with each of the first-mentioned beams, said stabilizer beam portions being spaced apart transversely of said plane and having cross-sectional areas substantially negligible with respect to cross-sectional areas of the first-mentioned beams, all of said beams being subject to bending stresses both by said moment and by said force and having oppositely located surfaces thereon placed respectively in tension and compression by such bending stresses, said beams being so proportioned in relation to each other and to the distances of said beam structures from said moment center to exhibit at respective predetermined measuring locations on said surfaces substantially complete mutual cancellation of stress components contributed by such transverse force, and strain-sensing elements mounted on said surfaces substantially at said predetermined measuring locations, respectively, thereby to sense components of stress in said beam structure contributed solely by said moment.

2. The force measuring device defined in claim **1** wherein said device comprises a strain gauge balance for aerodynamic model testing, said balance including an elongated cantilever having a base, a model supporting tip, and an intermediate instrument portion, said instrument portion having a moment center, axial force measuring means located at said moment center and transverse load measuring means spaced longitudinally from said moment center and comprising said beam structure.

3. The strain gauge balance defined in claim **2** wherein said stabilizer beam portions comprise separate beams spaced from said first-mentioned beams transversely of said plane.

4. The strain gauge balance defined in claim **2** wherein the outwardly facing surfaces of said stabilizer beam portions substantially are flush with outwardly facing surfaces of said first-mentioned beams.

5. The strain gauge balance defined in claim **2** wherein said stabilizer beam portions are positioned to have their respective individual centroids aligned transversely of said plane with individual centroids of said first-mentioned beams.

6. The strain gauge balance defined in claim **2** wherein said stabilizer beam portions are joined to opposite sides of said first-mentioned beams, respectively, thereby forming a pair of individual beams each having cross-sections along at least a portion of its length which include mutually perpendicular sections, one such section being disposed in said plane.

7. The strain gauge balance defined in claim **6** wherein each of said individual beams has a substantially cruciform section along at least a portion of its length.

8. The force measuring instrument defined in claim **6** wherein each of said individual beams has a cross-section of substantially I-beam configuration along at least a portion of its length.

9. The strain gauge balance defined in claim **6** wherein said individual beams are spaced apart in a horizontal plane and have strain gauges mounted thereon to measure yawing moment and side force, said beam structure further including an additional pair of measuring beams transversely spaced apart in a vertical plane and having strain gauges mounted thereon to measure pitching and rolling moment and normal force acting on said balance.

10. The strain gauge balance defined in claim **9** wherein said additional measuring beams have approximately elliptical cross-sections with their major axes in said vertical plane, thereby to minimize interaction of stress components in said additional beams, and wherein said individual beams have end portions of substantially cruciform cross-section and intermediate connecting portions of substantially rectangular cross section, thereby to minimize interaction of stresses in said individual beams.

11. In a strain gauge balance, a transverse load measuring section including pairs of substantially parallel measuring beam structures, the individual beam structures of at least one pair each having a substantially cruciform cross section along at least a portion of its length.

12. In a strain gauge balance, a transverse load measuring section including pairs of substantially parallel measuring beam structures, the individual beam structures of at least one pair each having a cross section along at least a portion of its length which includes mutually perpendicular sections, one section being disposed in the plane of loading.

13. The strain gauge balance defined in claim 12, wherein said beam structures are of substantially I-beam configuration.

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