Amplifying Ribbon Extensometer for Measuring Film and Fabric Strain

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Variations of a low-cost amplifying linear threshold extensometer (patent applied for) are presented in detail for high- or low-strain applications. Derivations of scale relationships and extraction forces are included with experimental correlations and analyses given on performance, attachment problems, gain selection, gage and base material compatibility, and zero setting techniques. Flight applications of unamplified gages on parawing deployment tests are noted. The amplified gages perform accurately in laboratory tests and further experience is needed on performance under dynamic environments.

Introduction

THE accurate measurement of strain on flexible membranes and/or fabric surfaces has long been a challenging objective. Numerous devices have been developed that, in general, have over sophistication, bulk, size, and mass inconsistent with the base upon which they are attached. The reliability and life of many such devices are far below those of the low-strain metal strain gages.

Instrumentation Need

Recent interest in rediscovering the lighter-than-air vehicles and expanded uses of decelerators merit parallel developments in related instrumentation. Both the old and new inflatable systems employ materials that are not readily amenable to test and measurement methods primarily intended for metals. Current concepts and active projects include dirigibles, semibuoyant aircraft, blimps, balloons, inflatable flying wings, aerial balloon cranes, logging balloons, airship gas carriers and farm produce carriers. Immense decelerators are being configured for recovery of space boosters and payloads and a significant industry has evolved in sport sky diving and parawing hang gliding. These and numerous other activities evolving around the structural use of fabrics, films, laminates, and composites will aggravate the quest for a variety of high-elongation strain measurement instruments.

While the high-elongation gage is primarily of value in the design and research functions, it is conceivable that such devices could be useful in numerous applications where maximum displacements or strain excursions are required for critical packaged items, and for recording and verification of maximum shipping dynamics on delicate packaged devices. Other possible applications are in the biomedical profession in measuring degrees of mobility and strain measurements of muscles.

Precedent Works

In the past several decades, isolated but dedicated efforts have been made to develop desirable high-elongation strain detection instrumentation suitable for application to lightweight and flexible base materials.

Hoffman,[1] describes the development and testing o commericially available, high metal elongation, foil strai gages designed for use on fabric. The conclusions were that i is feasible to measure biaxial fabric stress with foil gages if th experimenter is willing to accept high errors and induce strains are kept relatively low.

In Ref. 2, Mills gives details of a high-elongation strai gage developed by the Battelle Columbus Laboratory. Th gage consists of a rubber strip with small internal capillar tubes filled with liquid metal alloy. The resistance of th liquid metal changes with elongation and the gages functio and are wired in a manner similar to standard strain gage Other precedent works using liquid metal resistance chang were published by Whitney,[3] and Hurry et al.[4]

In Ref. 5, Crosby reports on the design and flight e perience of a fabric strain monitor. The monitor utilizes linear variable differential transformer (LVDT). The e tensive use of the gage has shown it to be reliable, sensitiv and accurate although it possesses the usual disadvantages size, height, bulk, and stiffening of the base fabric.

Mickey[6] describes a method of installing standard met strain gages on fabric. Strain-gage instrumented metal plat are attached to the fabric through stiff rubber pads whi permit a gradual transfer of the load from the material to t plates and a reduction in plate strain to the levels co mensurate to metal strain gages.

The Ribbon Extensometer

Germane to the subject extensometer is the nonelectri strain gage described by Ranes.[7] The gage consists of a leng of elastic material that has an inelastic thread attached to it one end. The other end has a bead or knot to serve as

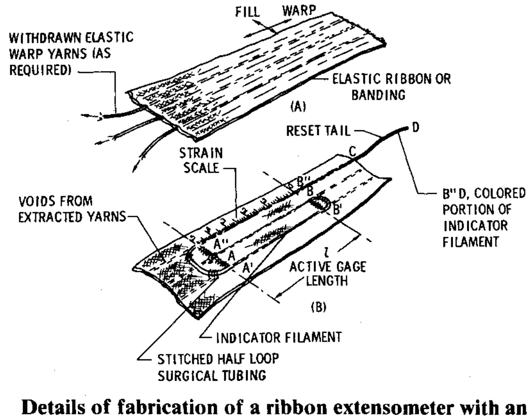

Fig. 1 Details of fabrication of a ribbon extensometer with an in amplification of three.

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indicator. As the substrate material stretches, the attached elastic band gage stretches but the thread does not. Movement of the bead or knot along a suitable scale indicates the total strain encountered.

The gage is simple and effective and provides adequate accuracy when installed on materials that experience large strains. Since the gage, as described, registers a one-for-one or unamplified strain measurement, the reading accuracy degenerates severely for low strains.

With a host of new materials of fabric and membrane construction but of low-strain characteristics, the unamplified extensometer is usually inadequate. In particular, new high-elastic modulus Kevlar materials will accentuate this low-accuracy characteristic. The nonelectrical strain gage developed by Ranes has been used to a limited degree in deceleration testing.

Amplified Ribbon Extensometer

It is the objective of this paper to document the details and some performance features of a high-gain or amplified linear extensometer. The gage is essentially passive, inherently low cost, of low mass and planar geometry, self-contained, and amenable to easy installation. It is reusable with reset capability. The high-gain feature allows manufacture in small sizes to permit detection of local strains. The negative feature of the gage is that it measures and preserves only the maximum strain.

A Simple Concept

One concept of the gage (Fig. 1) utilizes a highly elastic base ribbon such as the commercially available elastic bands used in garters, garments, and so forth that have straight elastic warp yarns. As many of the elastic warp yarns are removed as required by the amplification level to be obtained. The removed yarns are replaced by relatively inelastic yarns of any of a variety of textile materials. These filaments are henceforth defined as the "indicator filament."

The high-gain (or amplification) feature of the extensometer is made possible by the reeving system for the "indicator filament" as depicted on Fig. 1. Illustrated is a system that will yield an initial amplification of three (3) on strain experienced by the base ribbon. Figure 1a shows the extraction of three of the elastic warp yarns to allow for the rethreading of the inelastic "indicator filament."

Figure 1b shows one arrangement of how the "indicator filament" is threaded into the voids left from the initial operation of removal of the three warp elastic yarns. The replacement yarn (indicator filament) is entered at position A, threaded through the voided space and exits at point B. The distance AB is henceforth defined as the "active gage length." Then, the "indicator filament" is turned 180° around or through a semicircular tube, defined as the "half loop." Next, the "indicator filament" is reinserted at B' in the second of the voids left from the removal of the elastic warp yarns and threaded back over the "active gage length" to point A'. Here, it again exits and is turned 180° around a second "half loop" of suitable size to effect alinement with the remaining third void left by the third removed elastic warp yarn. Then, the "indicator filament" is reinserted in the third void space at A'' and threaded over the active gage length to point B'' and then continued until it exits the base ribbon at C. A tail CD is left of approximately the length of the active gage length that is useful for resetting the device, if so desired.

The indicator filament is dyed a different color (red or black) from point B'' to D than the color of the indicator filament from point A to B''. The color of the yarn from A to B'' is selected to be least noticeable by matching the color of the base ribbon. The filament is alined and secured by the knot at A such that the interface between the two colors on the indicator filament is alined with the zero of a strain scale printed on the base tape and when the base tape is in an unstrained position. The "zero" reference is taken at the B'' point. A suitable "strain scale" is printed on the base ribbon to permit direct reading of strain by observing the position of the color interface on the "indicator filament" relative to the printed scale.

Nonlinear Calibration

As the base ribbon is strained, the indicator filament will traverse over only a portion of the last loop ($A'' - B''$, free end). This has an effect on the instantaneous amplification or gain of the gage. The gain characterizing the gage is the instantaneous gain at the zero strain level. As the strain is increased, the gain diminishes. For example, for the case of 50% strain, the average gain is reduced to 2 for an initial system of gain 3 (case illustrated, Fig. 1). This facet of the strain calibration results in a nonlinear scale calibration and the relationship is derived as follows:

Let

- r = the unstrained dimension (or reading) between the B'' zero and the color interface of the indicator filament
- p = the equivalent dimension to r except under strain
- $\Delta\ell$ = increase in length of the gage length ℓ due to strain
- k_i = instantaneous gain at strain
- k_0 = nominal gain (or amplification) of the gage at zero strain
- ℓ = unstrained gage length
- ϵ = unit strain

Figure 2 further defines the dimensions of interest for a general k gain system

For a k_0 gain system of initial gage length ℓ the filament length to the color interface is "$k_0\ell$".

When the gage is strained to B''' for an incremental length increase of $\Delta\ell$ the gap p is generated by the filament's inability to extend in length. The color interface location is obtained by summing the lengths over which the filament does extend and equating the sum to the actual filament length, "$k_0\ell$."

$$(k_0-1)(\ell+\Delta\ell)+\ell+\Delta\ell-p=k_0\ell \tag{1}$$

Collecting terms and noting that

$$\epsilon=\Delta\ell/\ell \tag{2}$$

and

$$r(1+\epsilon)=p \tag{3}$$

then the relationship of strain to the unstrained indicator measurement r is

$$r=k_0\ell\epsilon/(1+\epsilon) \tag{4}$$

valid for strains where

$$\epsilon \leqq 1/(K_0-1)$$

For applications where strains will cause exceedance of the inequality, the indicator filament will unthread at the A'' half loop and a special interpretation of strain would be required.

The instantaneous gain is defined as

$$k_i=(1/\ell)(\mathrm{d}r/\mathrm{d}\epsilon) \tag{5}$$

and after performing the differentiation, it is seen that

$$k_i=k_0/(1+\epsilon)^2 \tag{6}$$

and has the same constraint as Eq. (4).

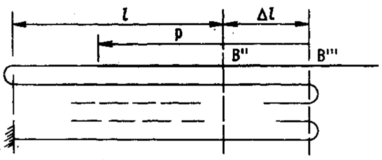

Fig. 2 Basic dimensions.

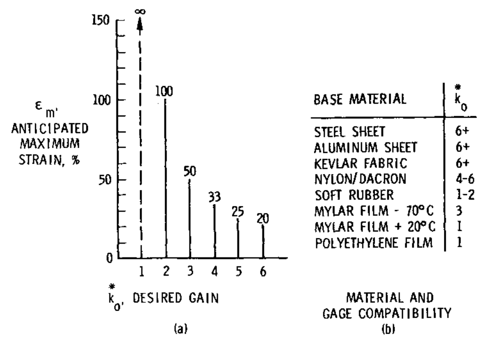

Fig. 3 Desired gain vs anticipated strain.

For $k_0=3$ and $\epsilon=0.5$, the instantaneous gain is 1.333. In other words, a change in strain will produce 1.3 times the change in the ratio r/ℓ. However, the average gain for the 0.5 strain level is 2.0 (i.e., for a 50% change in gage length the indicator travels 100%). For near zero strains, the instantaneous gain is slightly less than or equal to three (3). Thus, the maximum sensitivity is where it is most needed (for small strains).

Selection of Amplification Factor

Inherent to the selection of amplifying extensometers is the feature of selective gain (or amplification). For maximum sensitivity, the gage gain should be selected to yield nearly full-scale (gage length) reading for the maximum expected strain of the structural system being measured. Hence, it is desirable, for full-scale use, that $r/\ell \rightarrow 1$. Setting $r/\ell=1$ in Eq. (4), letting $\overset{*}{k}_0$ denote the desired gain for maximum strain ϵ_m, there results

$$\overset{*}{k}_0=(1+\epsilon_m)/\epsilon_m \qquad (7)$$

Solving Eq. (7) for ϵ_m for practical integer values of k_0 yields the gage selection data for Fig. 3a.

Observe, that for $\overset{*}{k}_0=1$, Eq. (7) yields nonsensible results except for $\epsilon_m=\infty$. This is a correct mathematical analogy to the fact that without amplification it is impossible to obtain an indicator filament reading equal to the gage length for finite values of strain. The ability of any of the amplified systems to use fully the available indicator displacement of $r=\ell$ is a plus feature for the amplified extensometer to be noted.

On Fig. 3a, full-scale measurements ($r/\ell=1$) are related to maximum anticipated strain. If the gage is to be installed on Dacron fabric having a possible 25% maximum strain, then a $\overset{*}{k}_0=5$ gage is desirable. The tabulation on Fig. 3b suggests the desirable match between gage amplifications and some conventional flexible materials.

Other Configurations and Design Features

The garter band concept has been discussed in detail. Higher performance is possible from other concepts. The main objective in modified designs is to reduce internal friction in order to allow for higher gains. One adverse effect of friction is that it loads the filament causing filament elongation. A second effect of friction is to cause large extraction forces (the reaction of the gage to straining) that cause changes in the initial stress and strain distribution of the base material for which the gage is installed to measure. A third adverse consequence from friction is the difficulty encountered in maintaining the gage end attachment integrit under the large extraction forces.

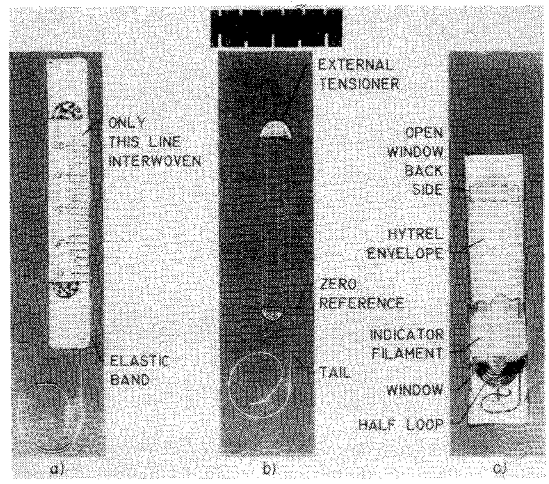

Fig. 4 Open-faced gages.

A feature of the ribbon gage is the encapsulation or hidde nature of the indicator filament within the base ribbon. Thi minimizes the possibility of disturbing or altering the recorde maximum strain by external factors such as wind, surfac abrasion, or dynamic motions. This encapsulation of th filament is at the expense of friction accumulation, and fc high gains, an unthreaded (or open face) or partially oper faced version of the filament installation is a necessity.

Open-Faced Gages

The "open-faced gage" refers to a type of amplifyin ribbon extensometer where the indicator filament is u threaded or only partially threaded in the base ribbon. Th type of gage is thought a necessity to acquire large an plifications, such as 10. Leaving all or most of the filamen free and unthreaded removes the interweave frictional forc that otherwise combine with and also increase the "half loop frictions. Gages of this type are shown in Fig. 4.

Figure 4a shows a $k_0=5$ partially open-faced gage wi only the indicator end of the filament threaded into the elast backing of the gage. Figures 4b and 4c are fully open-fac gages of $k_0=5$ and 10, respectively. The encapsulation e velope sleeve is essential to protect the exposed filament such gages and is made of a thin high-elongation membra material that requires little force to stretch.

Calibration Differences

The partially open-faced gage of Fig. 4a is calibrated accordance with the nonlinear scale relationship given by E (4) for the ribbon gage. The open-face gages of Figs. 4b a 4c do not comply with Eq. (4) since the indicator filament not restrained or entrapped in the elastic base and does n maintain its proportional position between the strained a unstrained conditions. Two methods of open-face cc struction that lead to different read-out interpretations a noted and illustrated in Fig. 5. The schematic of Fig. 5a sho the gage design where after maximum straining the filamen captured or constrained within the half-loop on the end of t zero reference. When this type of open-faced gage recovered, the filaments are unstretched and randon scattered as indicated by the relaxed diagram. To read t maximum experienced strain, it is necessary only to stretch t indicator filament and record the linear measurement p.

Equations (3) and (4) for the ribbon gage also are applica to the strained state of the open-faced gage of Fig. 5a. Th two equations yield immediately the relationship for str interpretation, simply

$$\epsilon=p/k_0\ell$$

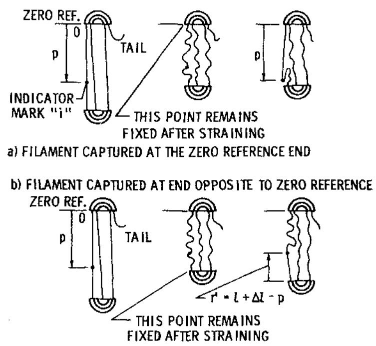

Fig. 5 Read out of open-faced gages.

(valid for open-faced gages with the filament constrained at the zero reference end).

The strain relationship for open-faced gages with the indicator filament constrained at the end opposite the zero reference is slightly more involved. If r' is the observed linear displacement of the indicator mark from the end opposite the zero reference, then

$$r' = \ell + \Delta\ell - p \tag{9}$$

But p is appropriately defined by Eq. (8) and recalling that $\Delta\ell = \epsilon\ell$ it follows

$$\epsilon = (1 - r'/\ell)/(k_0 - 1) \tag{10}$$

Also, for the continuosuly elastic constrained indicator filament for gages such as shown on Fig. 1, the strain is obtained explicitly from Eq. (4) as

$$\epsilon = (r/\ell)/(k_0 - r/\ell) \tag{11}$$

where r is the unstrained deflection of the indicator mark, or the ratio of r/ℓ can be acquired for any value of elastic strain (i.e., r and ℓ are then considered the instantaneous strained values).

Fabrication of High-Gain Gages

The heart of the high-gain gage is the "half loop." To acquire gains in excess of three, multiple spiral loops were wound, soldered, and separated into two 180° assemblies. A miscellaneous set of "half loop" pairs are shown in Fig. 6 for gains of 3, 5, and 10.

Loop Construction

The loops are actually spirals since the multiple reeving requires increasing radii for each consecutive wrap. The 10/1 loops are wound without spacing between the tubes to provide a minimum size. The 5/1 gage shown with omitted loops is an optional construction and allows easier attachment as well as alinement with the spacing of removed elastic warp yarns in the base ribbons. This spacing is not critical with open-faced gages. All of the experimental loops were fabricated from 1.27 mm (0.05 in.) o.d. Monel seamless tubing with 0.25 mm (0.01 in.) wall thickness.

The solid multiple loop fabrications are wound as a spiral and soft-soldered into an integral unit. This assembly is severed along a diameter, the cut line dressed with a file, and each hole countersunk to remove burrs and then burnished. A transverse cross bar is added that represents the gage reference line and attachment points. In some gages, vertical ears or tubular extensions are added to secure against out-of-plane motions. Also, in place of the transverse tubes, on some gages, attachment ears are provided.

Threading

The filament were threaded in the "half loops" by use of a 0.10 mm (0.004 in. diam) bobbit threader. A typical threading process uses three strands of Dacron thread with about a 4 per cm (10 per in.) twist and with a maximum bundle diameter of 0.64 mm (0.025 in.). The threading end is tapered by removing strands at the bobbit and then drawn through the 0.76-mm (0.03-in.) i.d. tubes. The threaded ribbon gage of Fig. 1 requires simultaneous threading of the loops and the voids from the extracted warp yarns of the elastic band base. Open-face gages do not require this interface.

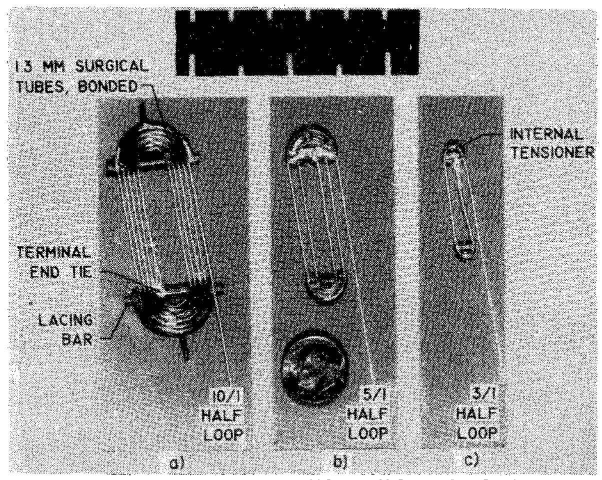

Fig. 6 Fabricated "half loops" for gains 3-10.

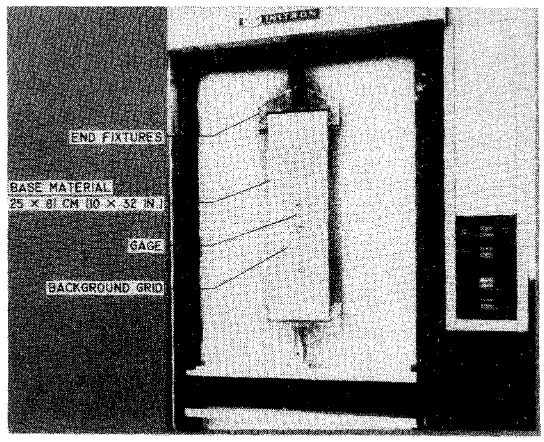

Fig. 7 Test assembly.

Cover Envelope

For the open-faced gages a 400% elongation material, such as Hytrel or rubber dental dam, is used as a packaging envelope. This flexibility permits ready zero setting and attachment even after enclosure.

Gage Attachment to Base

The finished and encapsulated gage is sewed or laced on the base material that is to be the strained medium. The lacing is done under reasonably well-regulated tension across the transverse tubing and ears provided for securing and establishing the gage length. The gage theoretically should attach only along the line indicated by the transverse tube. The vertical extension tubes (or ears) are lightly laced to allow longitudinal slippage but with transverse and out-of-plane constraint. All needle penetrations of the base material are closed by spot coating with an adhesive. If the gages are appropriately selected for the base material, the extraction forces will be such as to not exceed the strength and fixity provided by the lacing.

The application of adhesives is possible through the open-ended envelope (sleeve) and a direct bond to the base material is facilitated by a rectangular slot on the back side of the envelope at each lacing bar.

Transverse Interaction

In the elastic ribbon gage, transverse strains, if transmitted into the elastic base of the gage, will tend to squeeze, bend, or capture the filament. The significance of this effect is again dependent upon the interactive friction. Thus, it is concluded that improved gage performance is obtained by leaving the active gage length unsecured. In order to preclude undesirable motions during deployment and buffeting, a cover tape is necessary if the gage is not secured along the edges. A loose zig-zag stitch along the edges to secure the elastic envelope encapsulating the gage is thought helpful in maintaining the installation in position under adverse dynamic environments. The open-faced gage is inherently immune to the transverse effects.

Effective Gage Length

The theoretical gage length ℓ is pertinent to the interpretation of the gage read out as given by either Eqs. (4, 8, 10, or 11). The finite width and the degree of flexibility of the gage attachment lacing lead to some indeterminancy in defining the gage length. The reference length is basically the length between the centroids of the attachment pattern. Hence, it is important to maintain the pattern as close to a line configuration as possible to minimize the indeterminate features as well as to reduce distortion to the base material. Test data indicate the difference between the theoretical gage length and the distance between attachment centroids. This problem, when recognized, can be handled by simply calibrating after installation.

The Indicator Filament End Force

Most pertinent to the performance of the gage is the regulation of the tension force on the free end of the indicator filaments. A unique constant force device is epoxied in conformity to the outer half loop of the gage assembly usually (but not necessarily) on the end opposite the zero reference. This addition provides the controlled tension important to regulating extraction forces and preserving the indicator filament displacement after experiencing maximum strain. This tension regulator is not necessary to the threaded or partially threaded ribbon-type gage such as shown by Fig. 1 and Fig. 4a. However, it is a necessity for the performance of the fully open-faced gages as shown in Figs. 4b and 4c. Related analyses and experimental work follow on the tension and friction parameters.

Extraction Phenomena

In actual applications on fabrics and laminates, the gage extension force and the related base distortion along with attachment displacements produce gage inaccuracies and modifications to the stress field being measured. To confront these issues, analyses and investigations of extraction force phenomena were made. A variety of tests were performed on a standard Instron tester with specially devised end fixtures. The extraction and straining process was formulated and the analytical and experimental results correlated.

Test Apparatus

Strain tests on numerous gages of varied materials, construction, and gains were performed in the test assembly shown on Fig. 7. A standard model TTD Instron tester was used with strain applied at 0.5 cm/min (0.2 in./min) and with load sensitivities of 4450 N (1000 lb) full scale for Dacron base materials and 22250 N (5000 lb) full-scale sensitivity for Kevlar base materials.

The end fixtures accommodate cloth specimens of 25 cm (10 in.) width. The ends are secured by two 180° wraps and retainer bar. The fixture appeared in all cases to provide an undistorted end fixity with no evidence of slippage. Friction on the wraps precluded transverse motions of the specimen sides under load and resulted in the usual necking of the rectangular base specimen between fixtures. This was felt somewhat undesirable in that biaxial corner stresses were generated that are thought contributory to the premature failure of both the Kevlar and Dacron base materials tested.

The objective of the strain tests was to correlate gage indicated reading with known applied strain under representative attachment conditions and with base material distortions. The strain was determined by both Instron records and by background grid measurements with priority given to the latter.

Derivation of Extraction Forces

In Fig. 8 the idealistic force system of a filament threaded through a 180° "half loop" is shown. The only forces considered are the filament load in T_n and the filament load out T_{n+1}, the radial reactive load w and the related internally generated running friction, f.

Summing moments and radial forces yields, respectively

$$r(\mathrm{d}T/\mathrm{d}\lambda)\,\mathrm{d}\lambda - fr^2\mathrm{d}\lambda = 0 \tag{12}$$

$$wr\;\mathrm{d}\lambda - T\;\mathrm{d}\lambda = 0 \tag{13}$$

Recalling the friction relationship

$$f = \mu w \tag{14}$$

and with this and Eq. (13) it follows that

$$f = \mu T/r \tag{15}$$

Substituting Eq. (15) into Eq. (12) yields the following differential equation

$$\mathrm{d}T/T = \mu\;\mathrm{d}\lambda \tag{16}$$

whose solution is

$$T = \bar{c}e^{\mu\lambda} \tag{17}$$

when

$$\lambda = 0, \qquad T = T_n$$

$$\lambda = \pi, \qquad T = T_{n+1}$$

Therefore

$$\bar{c} = T_n \tag{18}$$

and

$$T_{n+1}/T_n = e^{\mu\pi} \tag{19}$$

Now the gage extraction force Q is the sum of all filament loads, that is

$$Q = T_1 + T_2 + \ldots T_{k_0} = T_1 + \left(\frac{T_2}{T_1}T_1\right) + \left(\frac{T_3}{T_2}\frac{T_2}{T_1}T_1\right) + \ldots\left(\frac{T_{k_0}}{T_{k_0-1}}\frac{T_{k_0-1}}{T_{k_0-2}}\ldots\frac{T_2}{T_1}T_1\right) \tag{20}$$

utilizing Eq. (19), yields

$$Q = T_1\left(1 + e^{\mu\pi} + e^{2\mu\pi} + \ldots e^{(k_0-1)\mu\pi}\right) \tag{21}$$

The series of k_0 terms enclosed in the parentheses is a geometric progression of ratio $e^{\mu\pi}$ whose sum is

$$\frac{Q}{T_1} = \frac{e^{k_0\mu\pi} - 1}{e^{\mu\pi} - 1} \tag{22}$$

Equation (22) provides the analytical expression for the extraction force of a gage of gain k_0 and of a filament end force

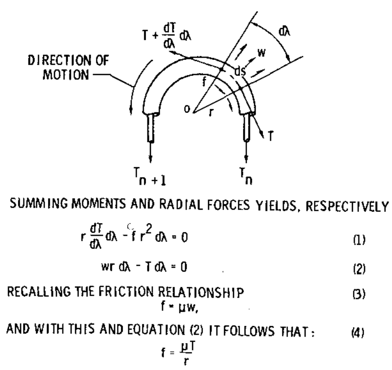

Fig. 8 Filament reactions.

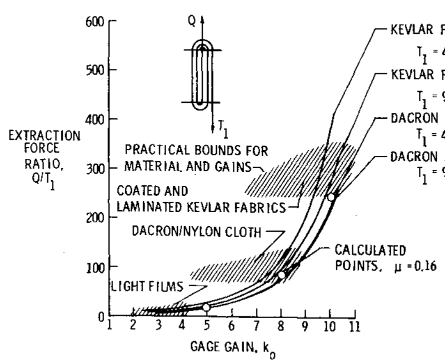

Fig. 9 Experimental and theoretical gage extraction forces.

of T_l and for the coefficient of friction μ. Observe that the extraction ratio Q/T_l is dependent only on the coefficient of friction and the gain constant of the gage. The limit of Q/T_l as $\mu \rightarrow 0$ provides the extraction force of a frictionless system, that is

$$\lim_{\mu \to 0} \frac{Q}{T_l} = \frac{0}{0} = \lim_{\mu \to 0} \frac{d/d\mu(e^{k_0 \mu\pi} - 1)}{d/d\mu(e^{\mu\pi} - 1)} = k_0 \qquad (23)$$

This is simply the rigging multiplication as would be expected and is a check of the degenerate case of Eq. (22).

For open-face gages where the indicator filament is free and consequently the filament end force T_l is zero, the filament constraint must be provided by a tensioner in the first or adjacent "half loop" (i.e., end opposite the zero reference, Fig. 5b.) Hence, T_l is essentially assumed to occur in the second reeved strand and the extraction force is computed from Eq. (22) for a gage of equivalent gain of "gain minus one," that is

$$k_{\text{eq.}} = k_0 - 1 \qquad (24)$$

The "gain minus one" advantage for configurations for which Eq. (24) applies is of considerable value for the higher gain levels. For example, the ratio of the extraction force of a "gain minus one" gage to the gage with the T_l filament end load is, from Eq. (22)

$$\frac{Q_{k_0} - 1}{Q_{k_0}} = \frac{e^{(k_0 - 1)\mu\pi} - 1}{e^{k_0 \mu\pi} - 1} \qquad (25)$$

If $k_0 = 10$, and for $\mu = 0.16$, $(Q_9/Q_{10}) = 0.60$

Hence, by simply configuring the $k_0 = 10$ gage, the extraction load is reduced 40%. From observations of such performance factors, the following design criteria have evolved. When observed, a design results that requires the least extraction force.

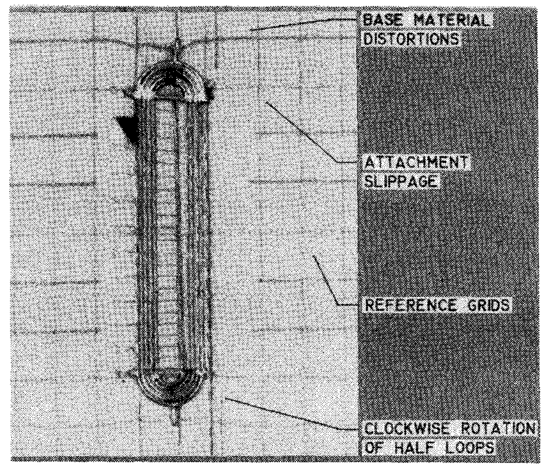

Fig. 10 Base distortion and gage attachment displacements resulting from improper gage-base match.

Design Criteria

1) For either even or odd gain open-faced gages, only $k_0 - 1$ "half loops" are needed and the tensioner is always opposite the zero reference. 2) For even gain gages, the tie-off (attachment point of filament) is on the gage end with the zero reference. 3) For odd gain gages, the tie-off is opposite the end with the zero reference.

For the ribbon-type closed-faced gage (i.e., such as Fig. 1) the filament end force T_l is generated inherently in advance of the first "half loop" and consequently the optimum design features are not applicable and the extraction force is in accordance with Eq. (22).

Analytical and Experimental Results

Measured data of Q for various values of the filament end force T_l have been made on the Instron for gains of k_0 equal 3, 5, and 10. These data are shown on Fig. 9 along with theoretical values from Eq. (22) computed for $\mu = 0.16$.

The Kevlar extraction force ratios were noticeably larger than those for the Dacron filaments. This is attributed to a near upper limit of filament area to available tube cross-sectional area for the Kevlar filament. This apparently introduced constriction forces as well as friction forces, causing functional differences between the idealistic force system leading to Eq. (22).

For full compliance with the theoretical formulation, the curves of Fig. 9 should be coincident and therefore independent of T_l. This is nearly the case for Dacron but shows less independence for Kevlar and for the reasons previously stated.

Proper Q/T_l Values

Also shown on Fig. 9 are practical Q/T_l regimes for Kevlar, Dacron, and film base materials. These bounds indicate the acceptable values of Q/T_l for filament end loads of about 4.5 g (0.01 lb) that would produce reactions over a 2.54-cm (1-in.) width approximating 1/100 of the ultimate membrane capacity of the types of materials noted. The value of 1/100, the ultimate capacity was chosen, based on experience as an acceptable and conservative distortion force to the base stress field and "half loops" while allowing an adequate filament end force T_l to maintain the fixity of the filament and for preserving the recorded strain.

Gain and Base Material Mismatch

Experiments of $k_0 = 10$ gages on 76 g/m² (2.25 oz/yd²) sail cloth clearly indicated the unacceptable distortions of the base material from the high gage extraction forces. (See Fig. 10.) Observe the distortion of the background grid in the vicinity of the gage ends. In addition, the stitching of the gage to the base was deformed causing an additional displacement of the

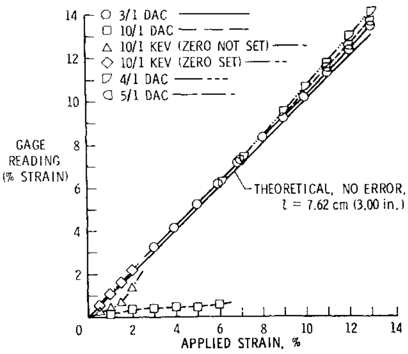

Fig. 11 Applied strain vs gage strain for various gains.

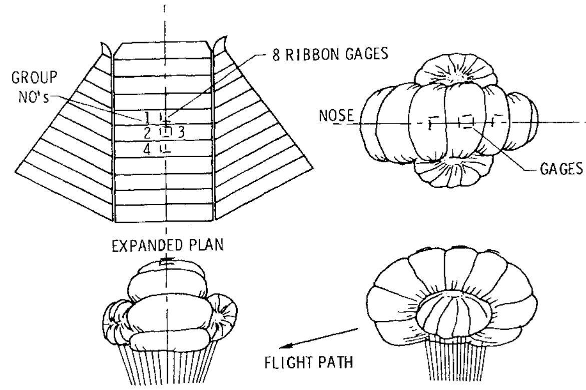

Fig. 12 Installation of ribbon extensometers on twin-keel parawing.

gage. The friction forces within the end fittings produce torque that caused the noticeable clockwise rotation of the "half loop" fittings. These effects produced the almost complete failure of the gage to extract and the resulting performance is shown on Fig. 11 as the 10/1 Dacron data for the square symbol and dashed line. The filament end load for the 10/1 Dacron gage test was 9 g (0.02 lb) which should indicate from Fig. 9 an extraction load ratio Q/T_l for the Dacron base material of about 215. The gage extraction force was equal to or greater than 4% of the unit membrane force in the base when the gage failed to perform.

Zero Setting

As seen on Fig. 11, the 10/1 gage on a Kevlar base (triangular symbol and dashed-dot line) also failed to produce adequate results. The base material was a two-ply 271 g/m^2 (8 oz/yd^2) coated laminate that is highly rigid by virtue of an internal fabric matrix of high modulus Kevlar. The material was thought good for approximately 4% strain at a failure load of around 600 to 700 N/cm (350 to 400 lb/in.). Premature failure, thought assoicated with biaxial end forces and lack of bias-weave side support in the test fixture, precluded a full assessment of this test. The gage and material were thought a proper match and no noticeable distortion of the base stress field was seen up to the 2.3% strain at failure. The filament end force T_l for the test was 4.5 g (0.01 lb) which should have produced an extraction force of around 9 N (2 lb), about the recommended 1%. These proper features lead to the conclusion that the poor gage performance was due to improper zero setting and perhaps some slack in attaching the end fittings.

The objective in zero setting is to remove internal slack without storing strain energy that can cause undesirable starting jumps in gage read out. It was observed and concluded that if zero setting forces applied to the filament exceed the internal extraction forces, the gage reading will read parallel but higher than the applied strain. Conversely, if setting forces are less than the typical extraction forces, the gage will read low. This behavior suggests that the gages be zeroed by first contracting the gage and applying negative indicated strain by tensioning the free end of the indicator filament, then stretch the gage with the appropriate extraction force indicated by data such as Fig. 9. This force is related to the end force and must be controlled by regulating as needed the filament end load, T_l. The zero should be set by displacing to the zero mark by coming from the negative strain direction.

The 10/1 Kevlar data on Fig. 11 (diamond symbol and dash-dot-dot line) is shown to illustrate the excellent results obtainable with an appropriately matched material to gain and by properly setting the zero.

Leading Strain Rate

Also shown on Fig. 11 are data for 3/1, 4/1, and 5/1 gain gages properly zeroed and on Dacron fabric. Observe that these data showed consistently a slightly leading strain rate above that of the theoretical line value. Upon a careful inspection of the gages, it was established that the effective gage lengths were slightly larger than the theoretical value used in deriving the gage scales causing the slightly higher indicated rate of strain read from the gages.

Flight Experience

The ribbon extensometer has been given only limited dynamic testing under actual flight conditions. A number of the unamplified gages (Ranes-type) were used for measuring deployment strains on approximately 20 drop-test experiments of parawings.

The typical flight configuration at first-stage deployment and with an eight-gage installation are shown on Fig. 12. Four sets of L pattern installation were used. The gages were of unit gain ($k_0 = 1$) of 12.7 cm (5 in.) gage length, and with an elastic band base of 18 cm (7 in.). The construction was similar to that of Fig. 1 (but without gain). No cover envelope was used and the gage was attached to the 76 g/m^2 (2.25 oz/yd^2) Dacron base material by loose cross stitches on 1.3 cm (1/2 in.) centers around the perimeter of the band. The parawings were hand packaged with care to keep all gages free from folds. The wings were drop tested from helicopters with controlled deployment dynamic pressures up to 490 kg/m^2 (100 lb/ft^2). Typical results from flight No. 308 are tabulated in Table 1.

Table 1 Typical results from flight No. 308

Group	Chordwise gages		Spanwise gages	
	Deflection, mm	Strain, %	Deflection, mm	Strain, %
1	5.2	4.1	3.7	2.9
2	6.4	5.0	5.2	4.1
3	3.8	3.0	3.7	2.9
4	5.0	3.9	10.2	8.0

The parawings were designed for low strain in order to provide good configuration control. It can be seen from the typical test data that only small deflections were recorded. The gages showed no damage from deployment and there was no evidence of false readings. The small recorded deflections indicate the desirability for amplifying sensors. Similar flight experience is needed to assess the performance of amplified gages to packaging, deployment dynamic pressures, buffeting, and high-strain rates.

Concluding Remarks

Concepts of a low-cost passive linear extensometer are presented that will amplify and measure and preserve the maximum strain encountered. The extensometer provides increased sensitivity and accuracy over predecessor unamplified passive systems and can be manufactured in smaller sizes with equal sensitivity. The inherent lightweight, planar geometry, and flexibility make the gage applicable to installations on films and fabrics. However, the high-gain feature makes it useful for installation on even conventional low-strain materials.

Scale relationships for various gage configurations are derived and the necessity for proper match of gage gain and base material stiffness is shown.

Considerable attention is given to internal friction as it limits the performance and upper levels of gain. The theoretical relationship for the gage extraction force is derived and compared with experimental data.

Methods of construction are given in detail along with a zero setting technique and the method of attachment to the base material.

Test data for gages of gains 3 to 10 are shown and the data proved beneficial in revealing attachment problems, gage and base materials incompatibility, zero setting techniques, effective gage lengths, and correlation of gage strain with base material strain.

In laboratory tests, when properly set to zero, installed with adequate fixity, and the gain matched with base material, the gages show accurate performance, generally reading within 1% strain at upper strain levels.

Flight experience has been had with the unamplified ribbon gage. Experience with the amplified ribbon extensometer in real dynamic environments is now needed.

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