Inverse Relaxation in Spun Yarns

R. P. NACHANE, G. F. S. HUSSAIN, G. S. PATEL, and K. R. KRISHNA IYER, *Cotton Technological Research Laboratory (ICAR), Matunga, Bombay 400 019, India*

Synopsis

This paper presents some experimental data on inverse relaxation exhibited by yarns spun from cotton, polyester, viscose rayon, and jute fibers. Inverse relaxation (IR) is the building up of tension in a viscoelastic material that has been allowed to recover a part of the initial extension it is subjected to. The IR index defined as a measure of the extent of this property has been determined at various levels of extension. A qualitative explanation of the results based on the fiber model proposed by Vitkauskas and Matukonis is also given.

INTRODUCTION

Time-dependant mechanical properties such as stress–relaxation, creep, creep recovery, etc. in textile materials have been subjects of detailed study in the past. But a closely associated property, namely, inverse relaxation (IR), seems to have received little attention. The term IR refers to the building up of tension in a material which has been allowed to recover a part of the extension initially given to it and then constrained to remain at that level of extension.

The occurrence of IR is often evident during cyclic loading tests as well as during the process of weaving. When a fiber specimen is initially loaded to a certain level and then the load is partly reduced, there would be an instantaneous recovery corresponding to the reduction in load. But the specimen may continue to contract over a period of time exhibiting what may be called "inverse creep" (this is to be distinguished from "creep recovery" that occurs when the load is removed altogether). Similarly, in the process of weaving, the yarns are subjected to periodically varying tensions, though, after being enmeshed in the fabric network, they are at relatively lower tension. If all the yarn segments have identical values of tension at any stage during the process and if their inverse creep (or relaxation) behavior is comparable, they would all contract by the same level. On the other hand, if the inverse creep (or relaxation) tendencies are dissimilar, a defective fabric could result.

Vitkauskas and Matukonis[1] initiated a study of IR by assuming a fiber model consisting of a spring in parallel with two Maxwellian elements, one of the elements having a period of relaxation many times shorter than the other. Later[2,3] these workers have derived a theoretical expression for stress in a fiber to explain the phenomenon of IR and have calculated the viscosity and spring constants for the chosen model by using experimental data on rayon and capron fibers. But they have not been able to establish the applicability of the theoretical expression which they had derived. On a quantitative basis the theory did not seem to stand the test of experiment.[3]

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The occurrence of IR in cotton fibers and yarn was illustrated in a recent communication[4] from this Laboratory where detailed study of the phenomenon in different materials is under way. The present paper discusses some experimental data on yarns of cotton, polyester, viscose rayon, and jute. The use of fibers in the study would have been better in view of the fact that the phenomenon is dependent on fiber structure and that it is difficult to account for the influence of yarn geometry on the test results. However, since the variability in yarns is much less than in fibers, the work becomes considerably less tedious, and, for this reason, yarns have been employed in the present study.

EXPERIMENTAL

The samples selected were cotton yarn (50s spun from variety PSH), polyester yarn (50s spun from medium tenacity staple fibers), viscose staple yarn (35s count), and jute yarn (6s count). All the tests were carried out under standard atmospheric conditions (i.e., 65% RH and 27°C temp) on the Instron Tensile Tester.

Determination of Inverse Relaxation

On the basis of preliminary tensile test data, four levels of extension were selected for the first three yarn samples. For the jute yarn only three levels of extension were selected at its breaking extension was found to be very low (1.7%). From each level of extension, the specimen was allowed to retract to preselected levels, and the stress variation with time was observed for each retraction level. Figure 1 shows the typical curve of load vs. time in an IR experiment. *OA* corresponds to the extension $e{\cdot}t_1$ of the specimen in time t_1 resulting in a load W_1. Here *e* is the rate of extension which is 10% of the gauge length per min. The retraction $e{\cdot}\ (t_2\ -\ t_1)$ allowed to occur during the time t_1 to t_2 shown by *AB* reduces the load to W_2. The

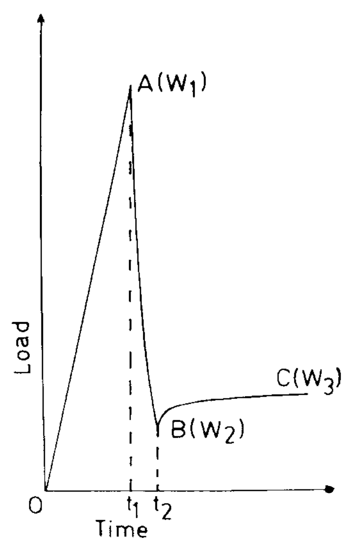

Fig. 1. A typical curve showing the load variation in a retracted specimen recorded on a time scale. The portion *BC* corresponds to inverse relaxation in the specimen.

specimen is constrained to remain at this extension of $e \cdot (2t_1 - t_2)$. The tension build up from W_2 to W_3 at this level of retraction during the interval t_2 to t_3 is represented by *BC*. The interval $(t_3 - t_2)$ was kept arbitrarily at 3 min as load increase thereafter was quite negligible. The ratio

$$\left[\frac{(W_3 - W_2)}{W_1}\right] \times 100$$ has been referred to as the inverse relaxation index (IR index).

Determination of Elastic Recovery

Immediate elastic recovery (IER), delayed recovery (DR), and permanent set (PS) were determined at selected levels of extension, by the ASTM procedure[5] with slight modifications. In Figure 2, *A* corresponds to zero extension and a load of tex/2 g on the yarn mounted on the Instron with a test length of 50 cm. The yarn is extended up to a predetermined level *B* and immediately retracted up to *O* the origin via point *F* on the tex/2 g load line. After allowing the yarn to relax for 3 min, it is again extended till it crosses the tex/2 g load line at the point *G*. If *BE* is perpendicular to the tex/2 g line, *AE* denotes the total extension, *FE* is termed as immediate elastic recovery, *GF* is delayed recovery after 3 min, and *AG* is the permanent set. The tex/2 g load line was selected for length measurements since it gives unambiguous values of length. Also, the yarn length is normally measured at tex/2 g load to take care of the crimp in it.

Qualitative Explanation of the Phenomenon

Let us consider the model proposed by Vitkauskas and Matukonis[1] as shown in Figure 3. Here the specimen is represented by a spring in parallel with two Maxwellian elements. Element S_1D_1 has a relaxation period much shorter than the element S_2D_2. Tension in the specimen at any instant of time is $T = T_1 + T_2 + T_3$, where T_1, T_2, and T_3 are tensions in the springs S_1, S_2, and S_3, respectively. In the process of continuous deformation of the system, the extensions in the springs S_1 and S_2 do not occur at the same rate as that in S_3 because the plungers in the dashpots are also in motion. The movement of dashpots gives a much lower rate of extension for S_1 as compared to S_2, since the relaxation period of S_1D_1 is small as compared to that of S_2D_2. When the extension is stopped and the specimen

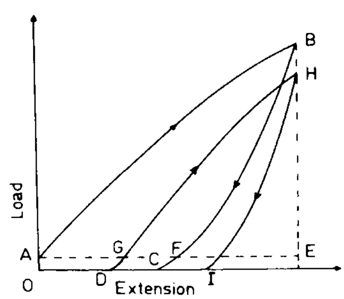

Fig. 2. Load extension cycles used for the determination of recovery parameters. *EF* denotes immediate elastic recovery, *FG* denotes delayed recovery, and *GA* denotes pemanent set.

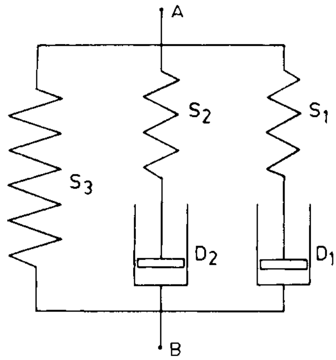

Fig. 3. Model explaining the phenomenon of inverse relaxation qualitatively.

is kept in this extended state, movements of plungers in the dashpots tend to make T_1 and T_2 zero. This corresponds to the stress–relaxation.

Now, if the specimen is retracted, the reverse movement of point B is superimposed on the upward movement of pistons in the dashpot D_1 and D_2. If the retraction is stopped at a level where S_1 and S_2 are still under tension, stress–relaxation would result. But, if the retraction is allowed up to a level where S_1 has already crossed its equilibrium position of zero tension and is instead compressed while S_2 is still in the extended condition, the load in S_1 would oppose that in S_2 and S_3. Thus the total load now would become $T' = T'_3 + T'_2 - T'_1$. But T'_1 becomes zero much faster than T'_2 on account of differences in relaxation times, giving rise to inverse relaxation in the beginning, followed by stress–relaxation, the latter being due to the fact that tension T'_2 in S_2 reduces to zero as time passes.

Figure 4 shows the stress variation in the material at different levels of retraction. If retraction is allowed up to the point A, there is only stress–relaxation as shown by curve AA'. If relatively high retraction is allowed up to the point B, there would be only inverse relaxation represented by BB'. At intermediate levels of retraction, the changes are characterized by an initial inverse relaxation, followed by stress relaxation (CC' and DD').

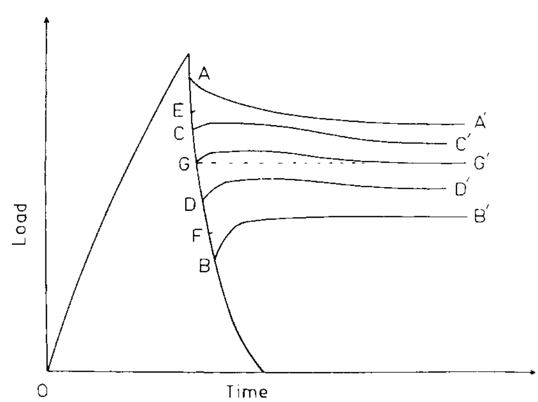

Fig. 4. Typical load vs. time curves of a specimen at different retraction levels corresponding to A, C, G, etc. EF represents the transition zone.

The intermediate retraction levels (*EF*) where both the phenomena are evident will be referred to in this paper as the "transition zone." The net gain or loss in stress suffered by the material would depend on the retraction level within the transition zone. For a level such as that corresponding to point G, the net stress gain after a long time will be zero.

If the retraction is allowed up to a point where both S_1 and S_2 are now compressed, S_1 being compressed more than S_2, the total load becomes $T'' = T''_3 - T''_2 - T''_1$. T''_1 and T''_2 both tend to zero, giving rise to increase in load over a period of time, corresponding to inverse relaxation.

RESULTS AND DISCUSSION

The results of IR measurements are given in Tables I – IV for cotton, polyester, viscose rayon, and jute yarns. Each sample with the exception of jute has been studied at four levels of extension, and at each value of extension the yarn was allowed to retract to a range of selected levels before the ensuing stress variations were measured. As can be seen from the values given in the tables, the IR index begins with a relatively high negative value at low retraction levels (signifying stress relaxation), and becomes positive for higher values of retraction.

Figure 5 shows the stress variation in a material which has been allowed to retract to a level within the transition zone EF referred to in Figure 4. As can be seen from Figure 5, in the transition zone there is a small increase in load after t_2, which corresponds to IR occurring in about 5 – 10 s. This load remain somewhat constant for a short interval (10–40 s) after which it shows a progressive decrease with time signifying stress–relaxation. After a few minutes, the load is more or less stabilized (C). The extent of inverse relaxation after t_2 goes on increasing, and the subsequent stress–relaxation goes on decreasing as the retraction level is increased. As a result, the net gain or loss ($W_3 - W_2$) in stress will depend on the position of point B in the transition zone *EF* referred to in Figure 4.

The two mechanisms, stress–relaxation and inverse of stress–relaxation, must be operating simultaneously in the retracted yarn. At low levels of retraction the former would predominate, giving negative values of the IR index. As the retraction is increased, inverse relaxation becomes more and more, leading to positive values of the IR index. The reversal occurs at a retraction level somewhat characteristic of the type of yarn. Beyond this reversal the IR index assumes progressively higher values, but again shows a downward trend and eventually reduces to zero. This occurs when the retraction level is beyond the combined elastic recovery (IER + DR) of the material for the particular extension level.

As the extension level is increased, the value of the IR index at zero retraction (i.e., stress–relaxation) is found to show a progressive rise, though in polyester there is an initial fall (between 2% and 4% extension levels) before the rise begins. The peak value of IR index shows an increase with increase in extension. However, at an extension level near break it tends to fall.

In the Vitkauskas and Matukonis model, use was made of four Maxwellian elements in parallel with a Hookean spring. The Maxwellian elements

TABLE I
Results for Cotton Yarn (50s Spun from Variety PSH)[a]

Ext. level = 2%, IER = 1.12, DR = 0.50, PS = 0.38		Ext. level = 3%, IER = 1.34, DR = 0.69, PS = 0.97		Ext. level = 4%, IER = 1.61, DR = 0.76, PS = 1.63		Ext. level = 5%, IER = 1.83, DR = 0.77, PS = 2.40	
Retraction level	IR index	Retraction level	IR index	Retraction level	IR index	Retraction level	IR index
0.00	-26.3	0.0	-26.0	0.0	-24.0	0.0	-22.4
0.10	-10.6	0.1	-10.7	0.1	-11.0	0.1	-10.4
0.20[b]	-2.0	0.2[b]	-4.2	0.2[b]	-5.4	0.2[b]	-4.9
0.30[b]	+0.9	0.3[b]	-0.2	0.3[b]	-0.8	0.3[b]	-0.9
0.40	3.8	0.4[b]	2.8	0.4[b]	1.9	0.4[b]	1.1
0.60	7.4	0.6	6.6	0.6	5.1	0.6	4.2
0.80	8.4	0.8	7.6	0.8	6.7	0.8	5.7
1.20	5.8	1.2	8.5	1.2	8.4	1.2	7.9
1.60	2.5	1.6	5.6	1.6	6.8	1.6	7.3
1.80	0.0	2.0	2.0	2.0	3.8	2.0	4.2
		2.4	0.0	2.4	1.1	2.4	1.4
				2.8	0.0	2.8	0.0

[a] Br. load = 241 g, Br. ext. = 5.8%, tex = 11.3, Tenacity = 21.3 g/tex, gauge length = 50 cm.
[b] Shows transition zone.

TABLE II
IR Test Results for Polyester Yarn (50s Spun from Medium Tenacity Staple Fibers)[a]

Ext. level = 2%, IER = 1.62, DR = 0.21, PS = 0.17		Ext. level = 4%, IER = 2.27, DR = 0.99, PS = 0.74		Ext. level = 8%, IER = 3.30, DR = 2.00, PS = 2.70		Ext. level = 12%, IER = 5.27, DR = 2.14, PS = 4.59	
Retraction level	IR index	Retraction level	IR index	Retraction level	IR index	Retraction level	IR index
0.0	-20.4	0.0	-25.8	0.0	-24.1	0.0	-17.7
0.1	-11.3	0.4[b]	-5.5	0.4[b]	-5.0	0.4[b]	-4.2
0.2	-7.0	0.6[b]	1.0	0.6[b]	-0.1	0.6[b]	-0.5
0.3[b]	-3.5	0.8	4.1	0.8[b]	2.8	0.8	1.7
0.4[b]	-1.3	1.2	8.8	1.2	7.2	1.2	4.9
0.6	2.7	1.6	11.0	1.6	9.3	1.6	6.4
0.8	4.3	2.0	11.9	2.0	11.1	2.0	7.0
1.0	5.0	2.4	11.1	2.4	12.2	3.0	9.1
1.2	6.2	2.8	8.0	2.8	12.5	4.0	9.4
1.6	5.0	3.2	5.5	3.2	13.0	6.0	4.1
1.8	3.9	3.6	0.0	4.0	9.4	7.0	1.0
2.0	2.1			4.8	3.9	8.0	0.0
2.2	0.0			5.6	0.5		
				6.4	0.0		

[a] Av. br. load = 292 g, Br. ext. = 14.9%, tex = 11.8, tenacity = 24.7 g/tex, gauge lengths = *t*50 cm.
[b] Shows transition zone.

TABLE III
IR Test Results for 100% Viscose Staple Yarn (35s)[a]

Ext. level = 2%, IER = 1.09, DR = 0.62, PS = 0.29		Ext. level = 4%, IER = 1.56, DR = 1.10, PS = 1.34		Ext. level = 6% IER = 1.86, DR = 1.38, PS = 2.79		Ext. level = 8%, IER = 2.10, DR = 1.52, PS = 4.38	
Retraction level	IR index	Retraction level	IR index	Retraction level	IR index	Retraction level	IR index
0.0	-38.4	0.0	-36.2	0.0	-34.6	0.0	-33.9
0.1	-21.0	0.2	-15.8	0.2	-15.4	0.2	-16.9
0.2[b]	-14.6	0.4[b]	-5.7	0.4[b]	-5.9	0.4[b]	-7.7
0.3[b]	-9.7	0.5[b]	-1.8	0.6[b]	-1.3	0.6[b]	0.1
0.4[b]	-1.6	0.6[b]	2.7	1.0	9.5	0.8[b]	5.2
0.5[b]	1.8	1.0	11.1	1.5	15.1	1.2	11.5
0.6[b]	4.7	1.5	16.6	2.0	18.1	1.6	14.5
1.0	12.4	2.0	17.2	2.4	16.7	2.0	16.8
1.2	13.9	2.5	6.5	2.8	10.4	2.4	17.4
1.6	7.6	3.0	0.0	3.2	2.5	2.8	15.6
1.8	3.1			3.6	0.0	3.2	9.4
1.9	0.0					4.0	0.0

[a] Av. br. str. = 153g, Av. br. ext. = 11.4%, tex = 17.0, tenacity = 9.1 g/tex, gauge length = 50 cm.
[b] Shows transition zone.

TABLE IV
IR Test Results for 100% Jute Yarn (6s)[a]

Ext. level = 0.6%, IER = 0.28, DR = 0.16, PS = 0.16		Ext. level = 1.0%, IER = 0.47, DR = 0.18, PS = 0.35		Ext level = 1.4%, IER = 0.69, DR = 0.19, PS = 0.52	
Retraction level	IR index	Retraction level	IR index	Retraction level	IR index
0.0	-30.7	0.0	-20.6	0.0	-17.1
0.1[b]	1.7	0.1[b]	-0.5	0.1[b]	-3.7
0.2[b]	3.3	0.2[b]	3.0	0.2[b]	0.0
0.4	2.8	0.4	4.1	0.3[b]	1.4
0.6	0.0	0.6	1.6	0.5	4.0
		0.8	0.0	0.7	3.2
				0.9	0.6
				1.1	0.0

[a] Av. br. load = 2.91 kg, Av. br. ext. = 1.74%, tex = 98, tenacity = 29.7 g/tex, gauge length = 50 cm.
[b] Shows transition zone.

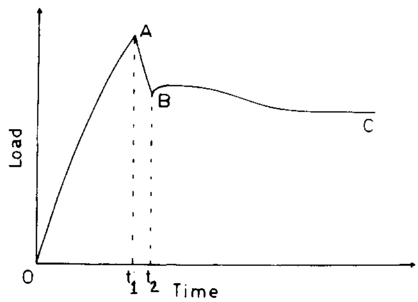

Fig. 5. A typical load vs. time curve when the retraction level falls in the transition zone.

have different relaxation times, but all the dashpots are governed by Newton's law of viscosity, i.e.,

$$f = \eta \frac{d\epsilon}{dt}$$

where f is force in the dashpot, ϵ is extension, and η is the viscosity constant.

As mentioned earlier, their derivation based on Newtonian dashpots did not seem to stand the test of experiment on quantitative basis.

It has been widely accepted that a dashpot governed by the hyperbolic sine rule derived by Erying, viz.,

$$\frac{d\epsilon}{dt} = K \sinh af$$

where K and a are constants, is far more satisfactory than the Newtonian dashpot. If this dashpot is used in Vitkauskas and Matukonis model, perhaps, a better result could be expected.

Since the present work is on spun yarns, such an attempt was not made, as yarn geometry besides the fiber properties would have influenced the calculations.

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