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SRB O-RING FREE RESPONSE ANALYSIS

By Dr. Carleton J. Moore

Structures and Dynamics Laboratory
Science and Engineering Directorate

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I. INTRODUCTION/SUMMARY

When O-rings are applied in thin shells applications, which are subjected to high pressure rates, the recovery characteristics of the O-ring material are of paramount importance. This paper identifies two different response mechanisms of viton O-rings and compares a theoretical representation of the two mechanisms with experimental results for various temperatures.

The test results for viton O-rings of the same composition as used with 51-L have been obtained from MSFC's Materials Laboratory. Analysis of the test results indicated that two different mechanisms are involved in the free response of O-rings. The initial 2 to 3 msec are dominated by an overdamped dynamic response, and the following response is then dominated by a classic creep equation as memory of the material tries to restore it to its original shape. In short, the viscoelastic materials take a set, which becomes the new short term equilibrium position, and then they slowly creep back toward the original position. This set position is influenced by time of compression and temperature. Analytical representation of these characteristics is required for determination of sealing and sealing margins in joint response analyses.

II. FORMULATION OF THE MATH MODEL

The math model formulation was intended to be of the simplist possible form and yet incorporate the most important phenomenon active in the response of the O-rings. The most important nonlinear effect in the O-ring response was found to be material nonlinearity. Although geometrical and boundary nonlinearities would have an influence, the general behavior is defined by the material properties.

The response of the O-ring can be defined simply by a single degree of freedom overdamped elastic response to a short term equilibrium set position which responds to the free creep equation.

$$x(t) = A\, e^{(-\zeta + \sqrt{\zeta^2-1})\omega_n t} + B\, e^{(-\zeta - \sqrt{\zeta^2-1})\omega_n t} + x_{sp}(t) \tag{1}$$

where

$$A = \frac{x(0) + (\zeta + \sqrt{\zeta^2-1})\omega_n\, [x(0) - x_{sp}(0)]}{2\, \omega_n \sqrt{\zeta^2-1}}$$

$$B = \frac{-x(0) - (\zeta - \sqrt{\zeta^2-1})\omega_n\, [x(0) - x_{sp}(0)]}{2\, \omega_n \sqrt{\zeta^2-1}}$$

ζ = critical damping > 1

$$\omega_n = \sqrt{\frac{K}{M}}$$

$x_{sp}(t)$ = x position of set position at time t .

Using both experimental compression data for 0.04 in. compression and a finite element model of the compressed O-ring, the equivalent stiffness for a 1-in. segment of 0.28 in. diameter cross section O-ring is as follows:

$$K = 812.5 \text{ lb/in.}$$

The density of viton was taken as 0.0506 lb/in.^{3} with the density of the aluminum test cover plate was taken as 0.1 lb/in.^{3}. The equivalent mass for a 1-in. segment with cover plate in this 1-deg of freedom model is as follows:

$$M = 4.035 \times 10^{-6} + 9.6885 \times 10^{-6} = 1.37235 \times 10^{-5} \frac{\text{lb sec}^2}{\text{in.}} \quad .$$

The short term equilibrium set position is controlled by free creep equation.

$$x_{sp}(t) = x_{sp}(0) - [x_{sp}(0) - x_f] \left(1 - e^{-C_R t}\right) \qquad (2)$$

where

X_f = X position of fully relaxed O-ring

C_R = creep retardation factor .

A simplification in this 1-deg of freedom solution is that the stiffness K is assumed linear while in reality it is nonlinear. The linear stiffness assumption seems to work because the problem is so heavily controlled by the material damping and creep behavior. The initial velocity and position of the experimental response tests were:

$$\dot{X}(0) = 0.0 \text{ in./sec}$$

$$X(0) = 0.04 \text{ in.}$$

The above definition of variables leaves only the definition of four important parameters. These parameters are short term equilibrium set position, the final relaxation position, the elastic critical damping, and the creep retardation.

The final relaxation position and the short term equilibrium set position are both compression time and temperature dependent. The top curve in Figure 1 is the final relaxation position for experiment points (at 2 min) taken at 110°F to 120°F. This is measured directly from response test data for viton compressed 2 hr at 0.04 in. compression. Experimental data also exists for varying compression times with temperatures of 25°F, 75°F, and 120°F.

Reduction of this test data will allow development of the first cut at characterizing compression effects. (It should be noted that the compression effects are also temperature dependent.) The experimental relaxation points versus temperature are reduced by a least squares fit of a second order equation.

$$X_f = C_{f_1} T^2 + C_{f_2} T + C_{f_3} \tag{3}$$

where

$$C_{f_1} = -2.3656 \times 10^{-6}$$

$$C_{f_2} = 5.238581 \times 10^{-6}$$

$$C_{f_3} = -3.149483 \times 10^{-2} \quad .$$

The lower curve on Figure 1 is the least squares fit of the experimental short term equilibrium set position. At 10°F the short term equilibrium set position is frozen at its fully compressed state so there is no elastic response at all but only a creep response to the above relaxation point. The fourth order fit equation, which relates set position at time, equals zero is as follows:

$$X_{sp}(0) = C_{sp_1} T^4 + C_{sp_2} T^3 + C_{sp_3} T^2 + C_{sp_4} T + c_{sp_5} \tag{4}$$

where

$$C_{sp_1} = 7.857057 \times 10^{-10}$$

$$C_{sp_2} = -2.64394 \times 10^{-7}$$

$$C_{sp_3} = 2.70266 \times 10^{-5}$$

$$C_{sp_4} = -6.309301 \times 10^{-4}$$

$$C_{sp_5} = -3.616922 \times 10^{-2} \quad .$$

It would be useful to experimentally investigate the response between the region of 75°F and 120°F because the lower curve of Figure 1 seems to indicate that there might be some transition in the material properties in this region. It is also interesting to note that 10°F corresponds to viton's glass transition temperature.

III. VARIATION OF ELASTIC CRITICAL DAMPING WITH TEMPERATURE

Figure 2 shows critical damping obtained from response curves for temperatures from 40°F to 120°F. There was so little elastic response at the lower temperatures that the elastic critical damping was not important and thus not reducible from the response tests.

A second order equation was least squares fit as follows:

$$\zeta = C_{\zeta_1} T^2 + C_{\zeta_2} T + C_{\zeta_3} \tag{5}$$

where

$$C_{\zeta_1} = .0522531$$

$$C_{\zeta_2} = -10.81597$$

$$C_{\zeta_3} = 604.5592 \quad .$$

IV. VARIATION OF CREEP RETARDATION FACTOR WITH TEMPERATURE

Figure 3 shows the creep retardation factor obtained from response curves for temperatures varying from 10°F to 120°F. It would be desirable to obtain additional test points between 75°F and 120°F.

$$C_R = C_{R_1} T^2 + C_{R_2} T + C_{R_3} \tag{6}$$

where

$$C_{R_1} = -8.590661 \times 10^{-5}$$

$$C_{R_2} = 1.425345 \times 10^{-2}$$

$$C_{R_3} = 2.539142 \times 10^{-2} \quad .$$

V. VITON (51-L) RESPONSE

Figures 4 through 11 show a comparison of experimental versus theoretical response as in equations (1) and (2). The good experimental to theoretical comparison across the temperature range seems to indicate that identification of the two basic phenomenon is right. These basic phenomena are an overdamped elastic response combined with a creep recovery. A theoretical to test comparison can be altered slightly by changing the equation and the surface fitting procedure for the temperature dependent parameters. Although the comparison is quite good, caution must be used in extrapolation of the results to cases other than a 0.28 in. diameter viton O-ring compressed 0.04 in. The basic parameters were obtained from test data for a single strain field. Additional basic materials research needs to be done to characterize the material for the general case.

This characterization would hopefully allow finite element models to successfully predict behavior of a viton sample of any size or shape with any set of boundary and force conditions.

VI. EXTRAPOLATION OF THEORETICAL MODEL TO INCLUDE PRERELEASE COMPRESSION TIME AND VARYING AMOUNTS OF INITIAL COMPRESSION

Although, as mentioned above, caution must be used to extrapolate the response model to anything other than 0.28 in. diameter viton O-rings compressed 0.04 in., it is possible to derive a mathematical model for a more general case. The basic model can be initially obtained by the following extensions and then revised and refined as additional test data becomes available.

The prerelease compression time response effects can be modeled by a displacement shift of both the short term equilibrium position and the final relaxation point. During the O-ring specimen compression, the viscoelastic creep takes place at a rate which looks comparable to the curve fitted creep recovery.

There is an additional phenomenon which takes place on a long term basis. This phenomenon seems to be a nonrecoverable creep which resembles a fluid flow. This phenomenon was characterized for 75°F, but more data is needed for a complete characterization. Around 10°F to 25°F this process of fluid flow stops, but, also the viscoelastic creep takes a significant set which is not recoverable at the low temperatures.

The variation in the amount of compression can be accounted for by relating the percent deflection of the short term equilibrium position and the final relaxation point. The elastic critical damping and the creep retardation factor would be assumed the same. This model would be conservative for deflections less than 0.04 in. and probably unconservative for deflections greater than 0.04 in.

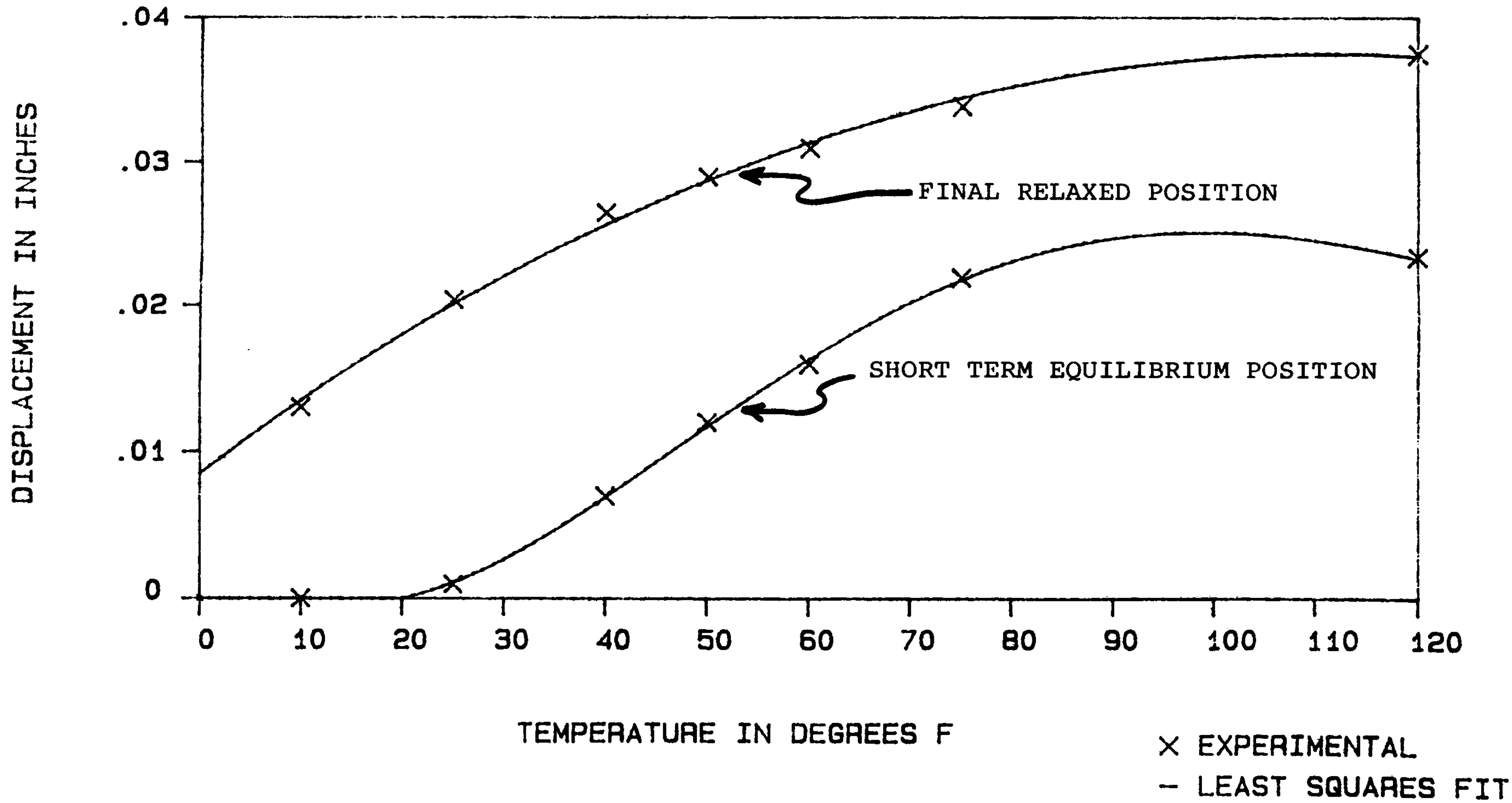

Figure 1. SRB O-ring relaxation and set position
Viton O-ring compressed 0.04 in. for 2 hr.

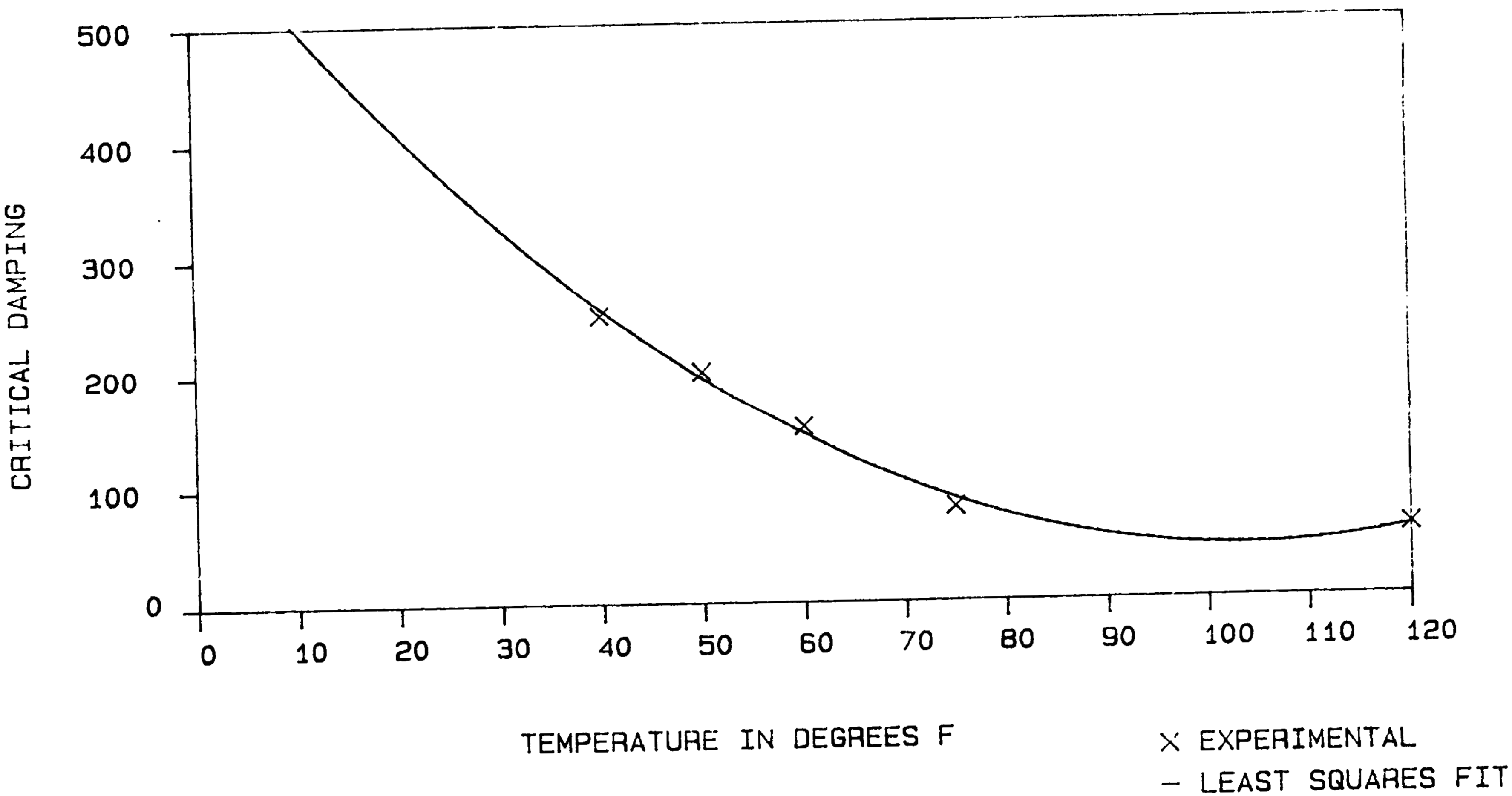

Figure 2. SRB O-ring elastic critical damping
Viton O-ring compressed 0.04 in. for 2 hr.

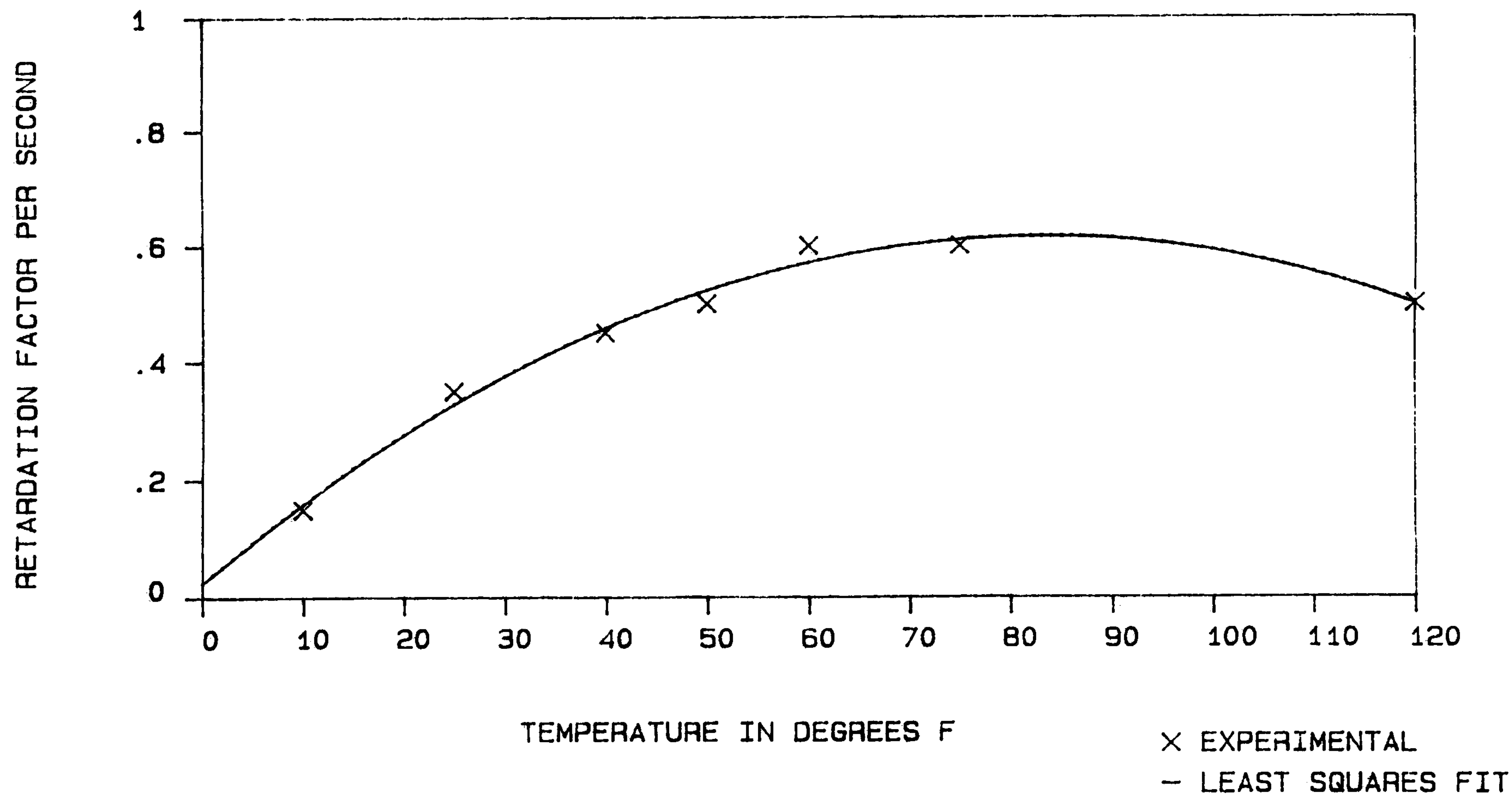

Figure 3. SRB O-ring creep retardation factor
Viton O-ring compressed 0.04 in. for 2 hr.

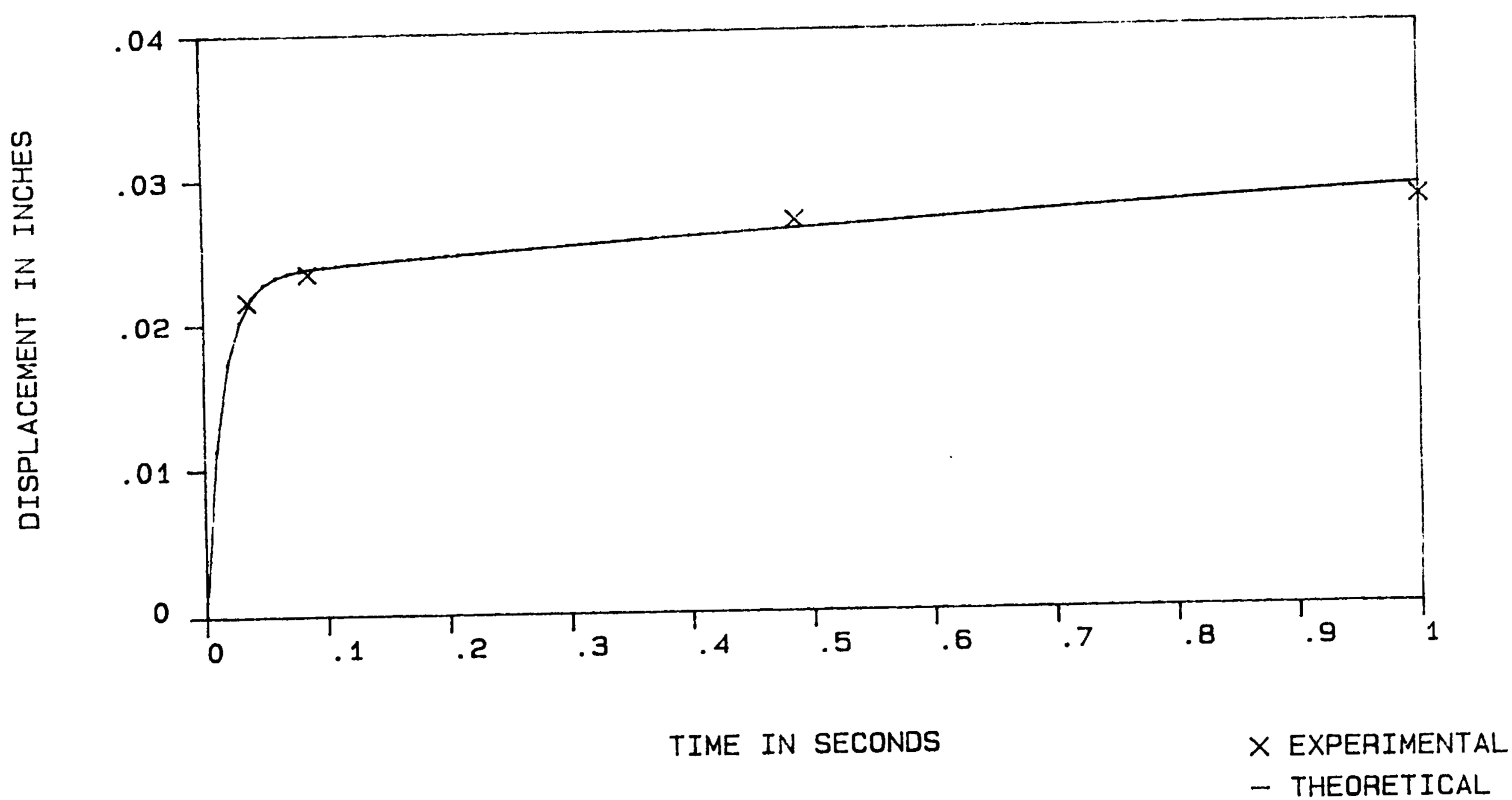

Figure 4. SRB O-ring free response, Viton O-ring compressed 0.04 in. for 2 hr, temperature 120°F.

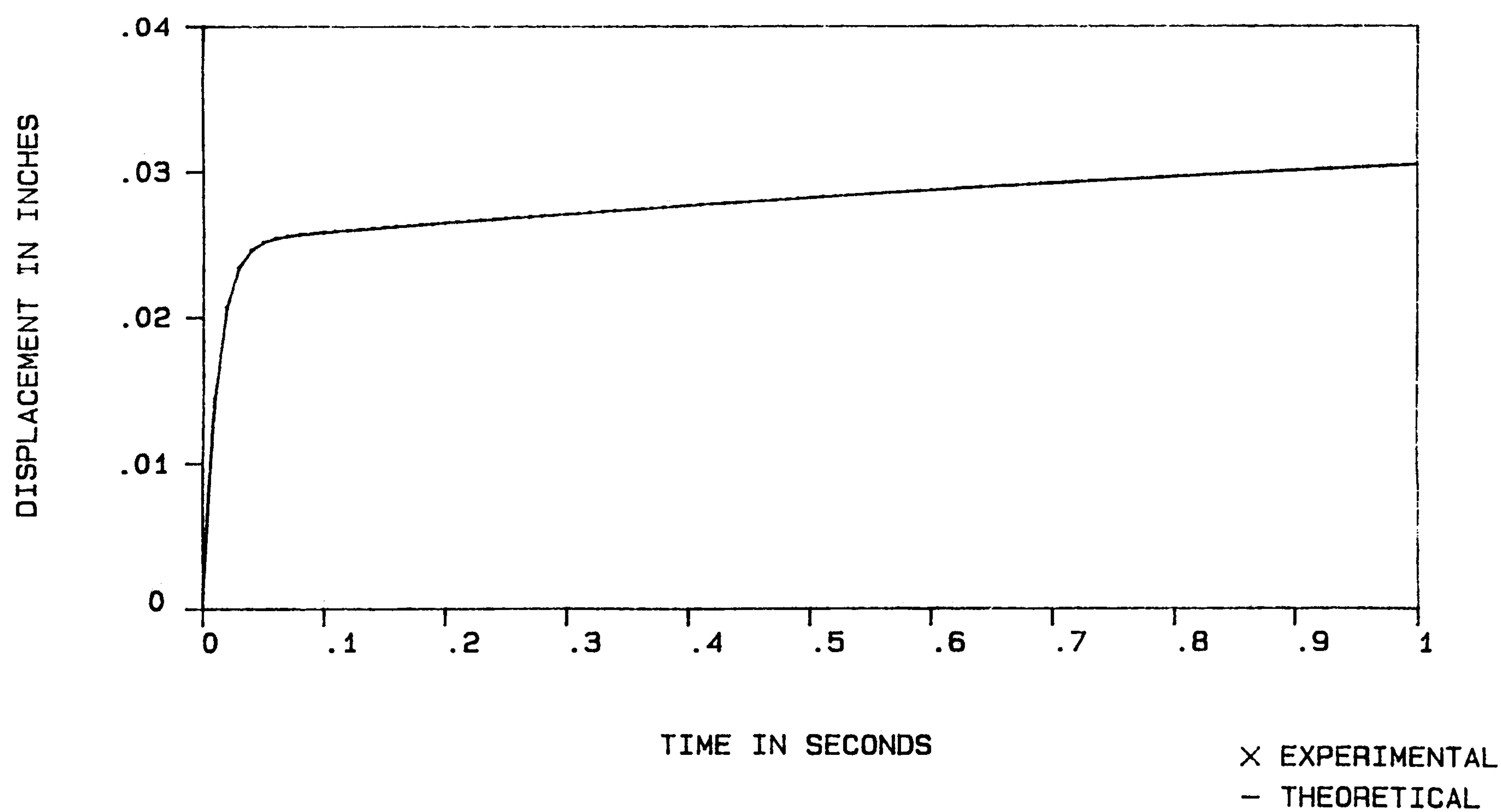

Figure 5. SRB O-ring free response, Viton O-ring compressed 0.04 in. for 2 hr, temperature 100°F.

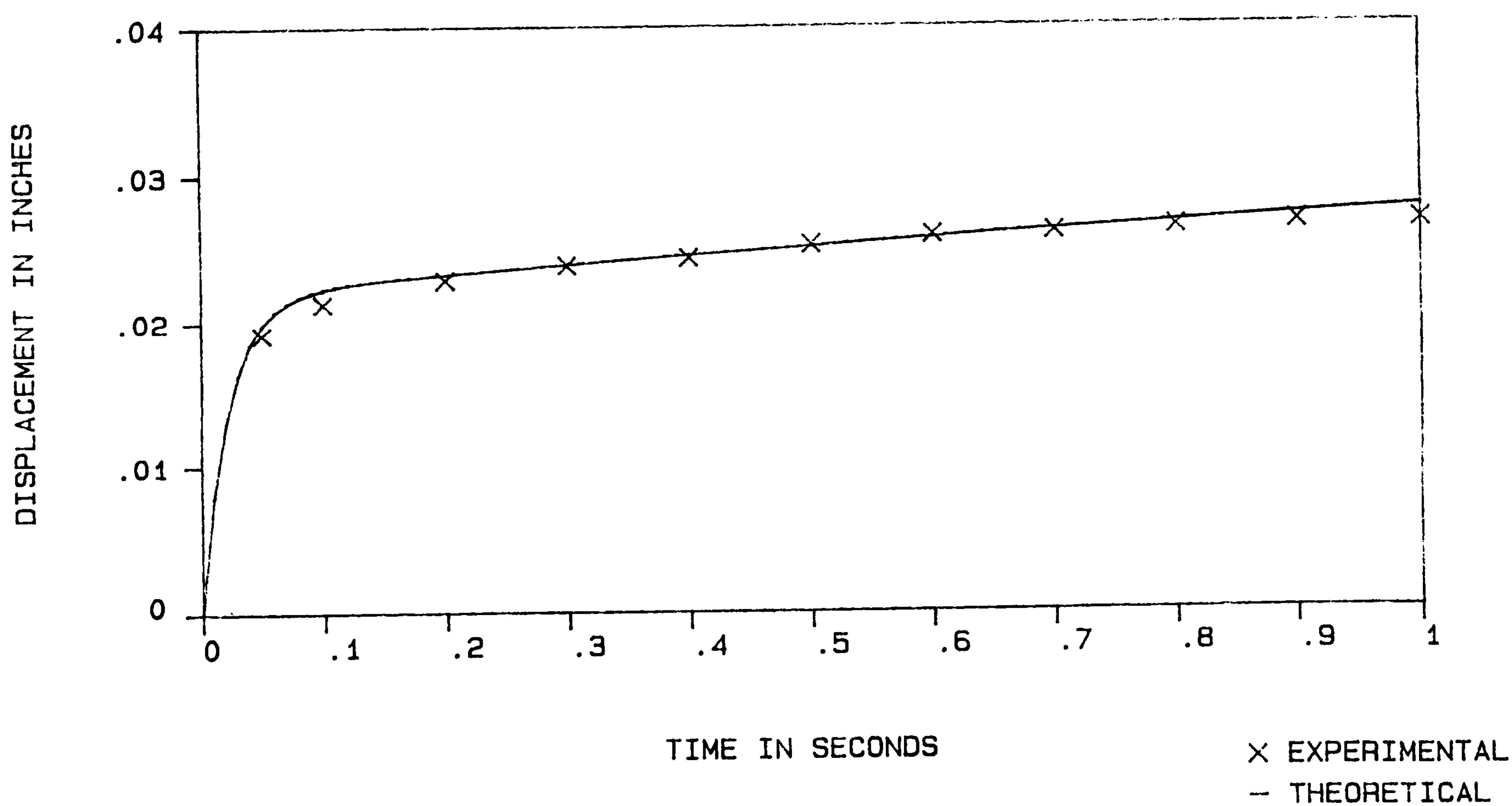

Figure 6. SRB O-ring free response, Viton O-ring compressed 0.04 in. for 2 hr, temperature 75°F.

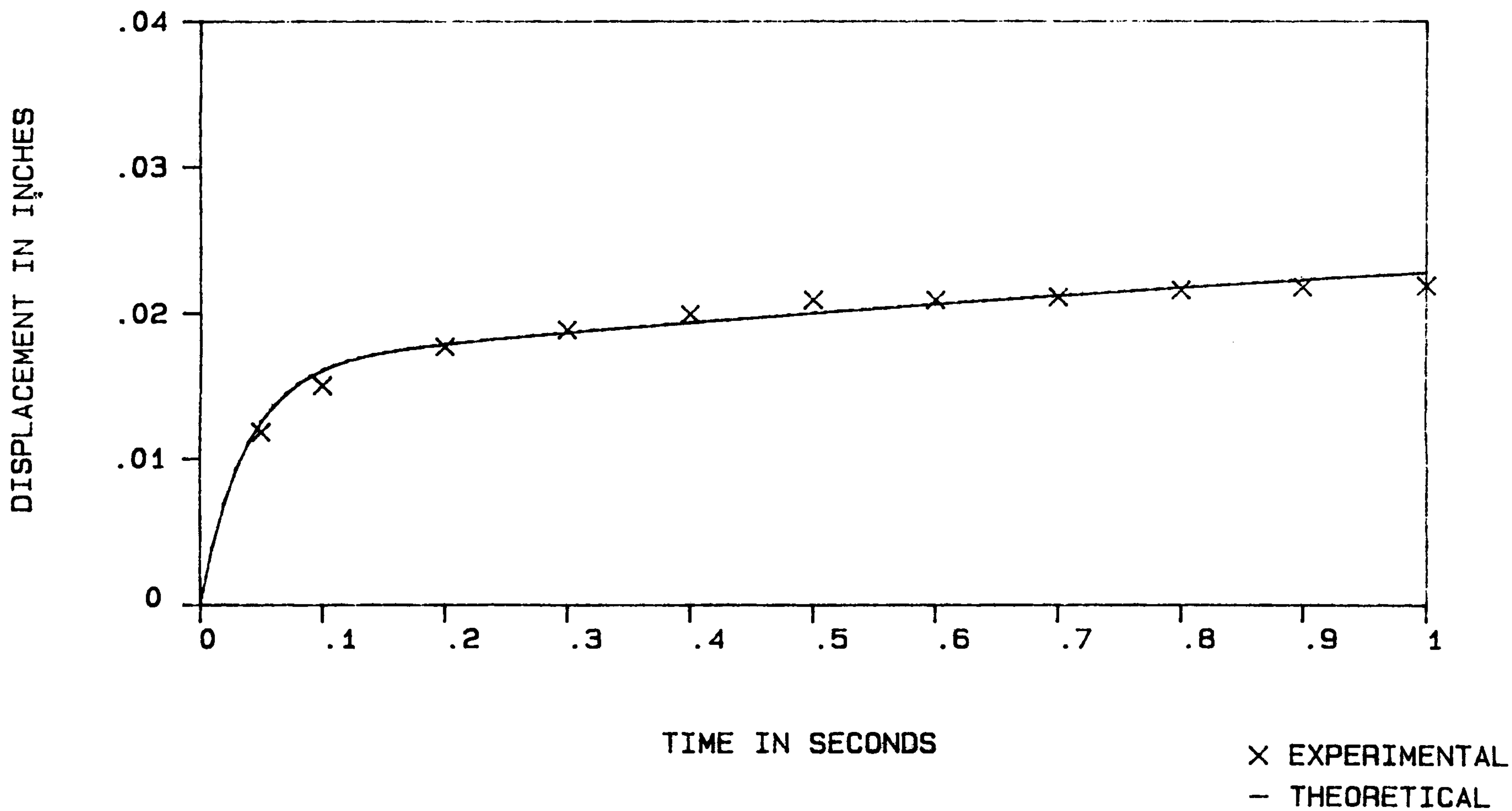

Figure 7. SRB O-ring free response, Viton O-ring compressed 0.04 in. for 2 hr, temperature 60°F.

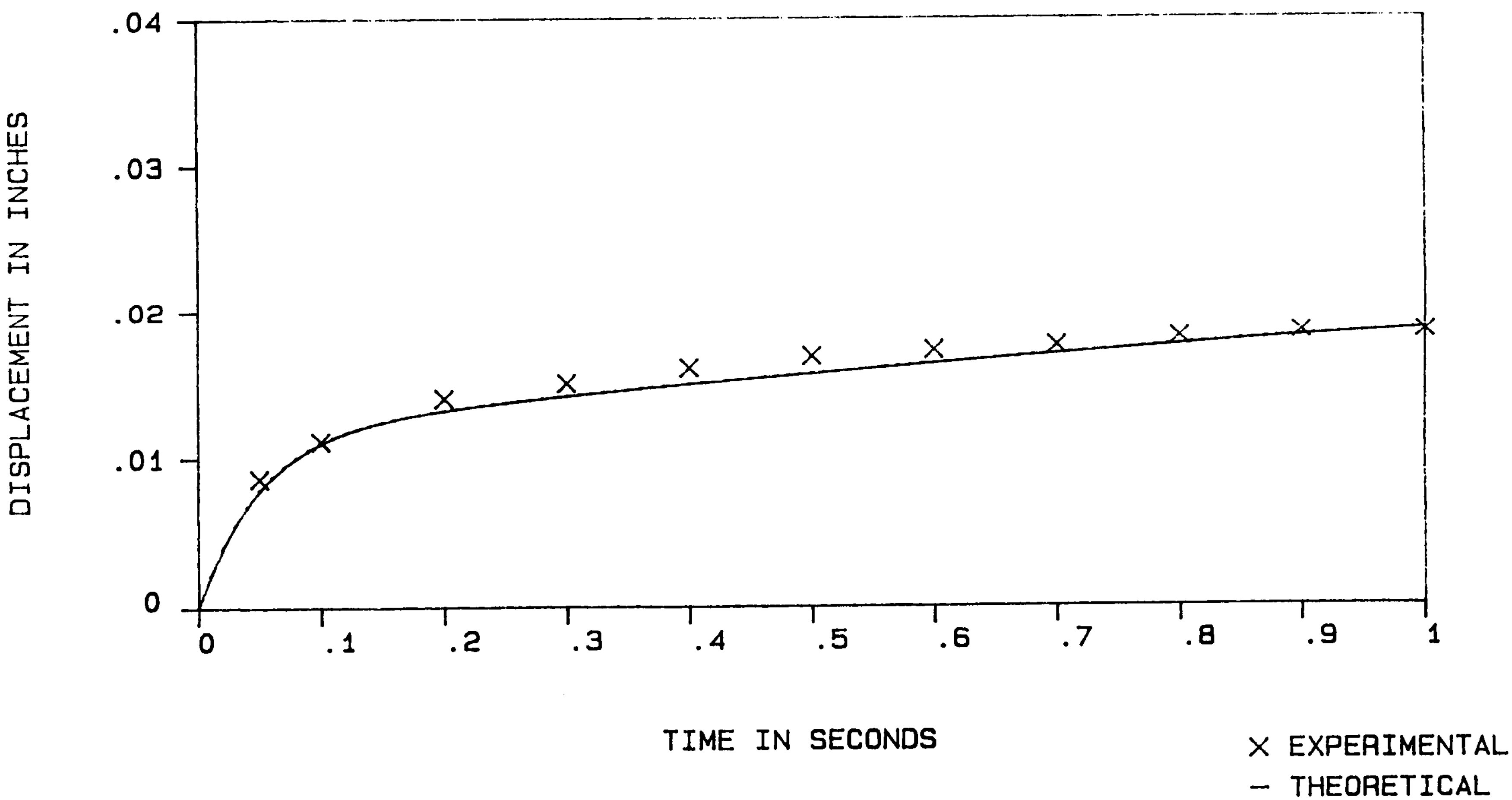

Figure 8. SRB O-ring free response, Viton O-ring compressed 0.04 in. for 2 hr, temperature 50°F.

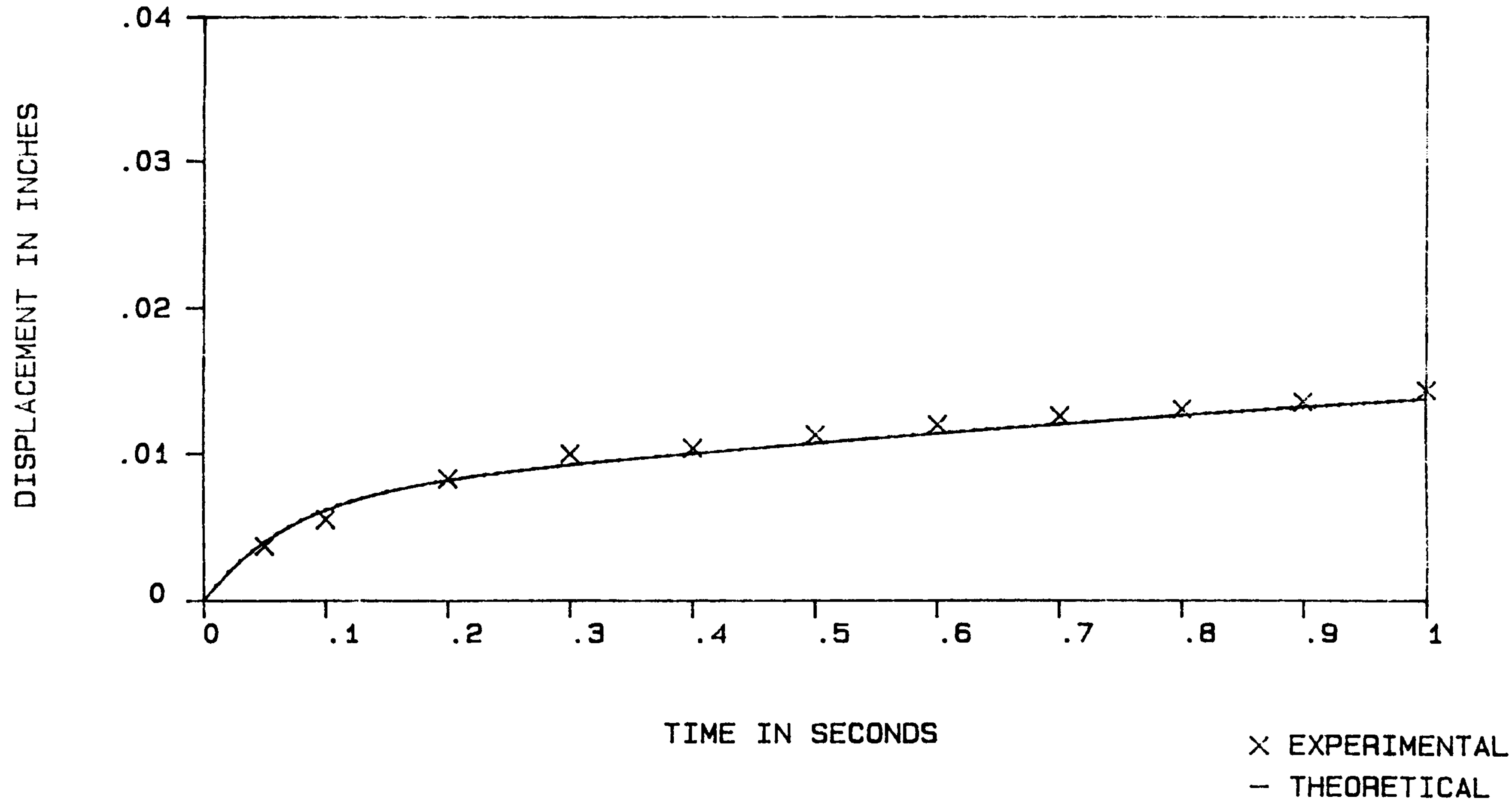

Figure 9. SRB O-ring free response, Viton O-ring compressed 0.04 in. for 2 hr, temperature 40°F.

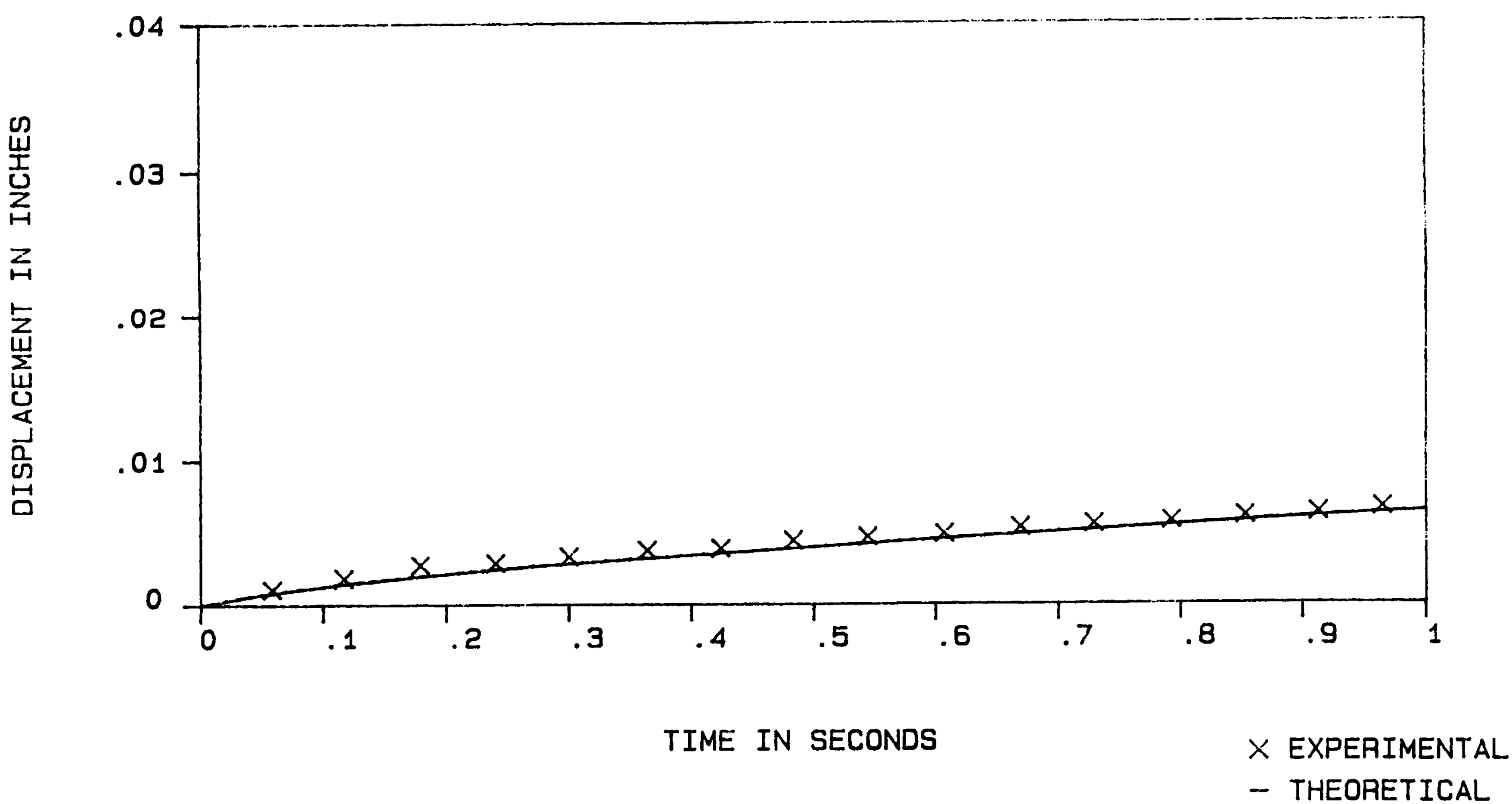

Figure 10. SRB O-ring free response, Viton O-ring compressed 0.04 in. for 2 hr, temperature 25°F.

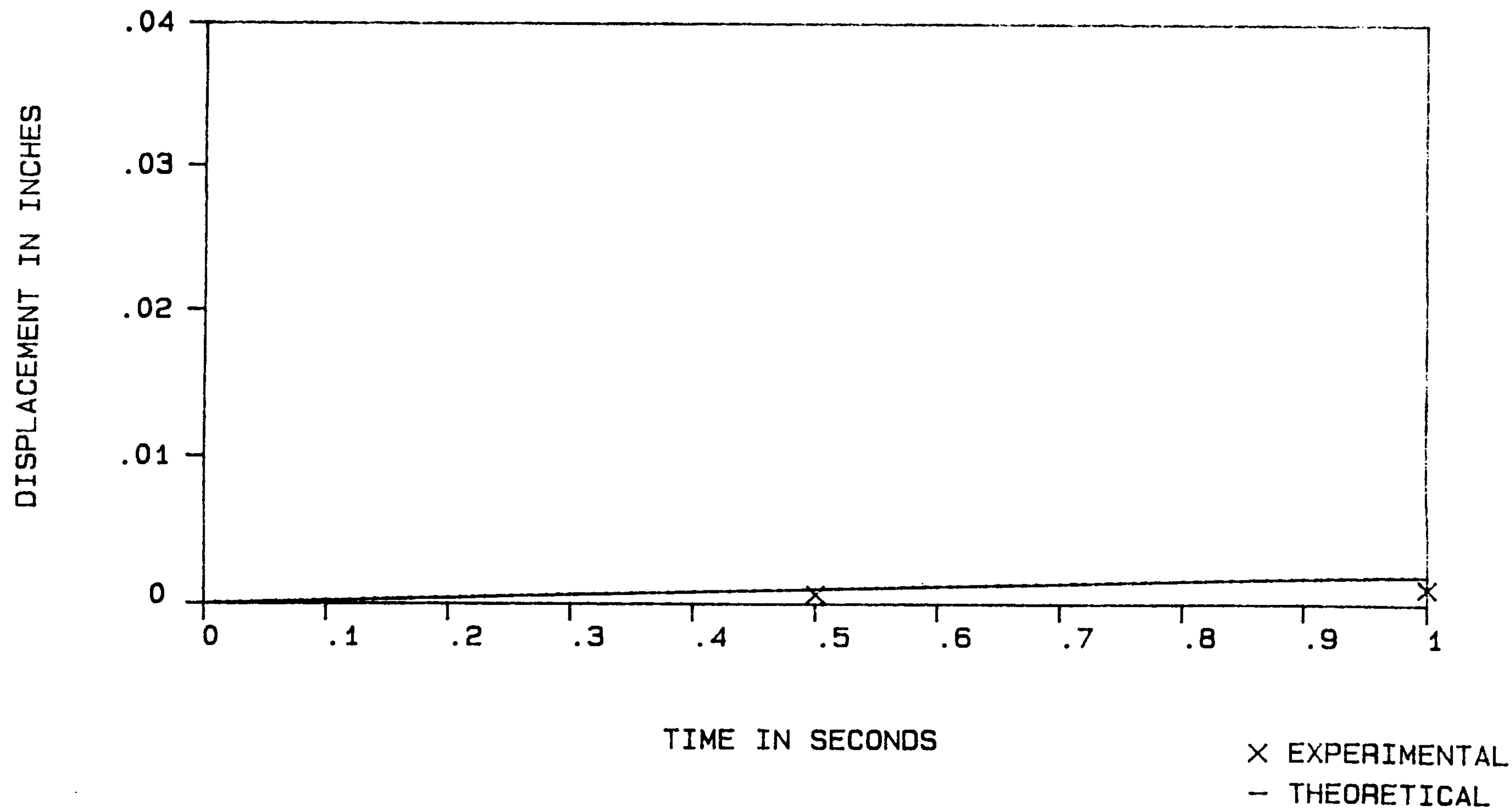

Figure 11. SRB O-ring free response, Viton O-ring compressed 0.04 in. for 2 hr, temperature 10°F.

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APPROVAL

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By Dr. Carleton J. Moore

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

G F McDonough

G. F. McDONOUGH
Director, Structures and Dynamics Laboratory

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16. ABSTRACT

This report investigates the free response of viton O-rings. Two different response mechanisms of viton O-rings are identified and a theoretical representation of the two mechanisms is compared with experimental results for various temperatures.

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