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ON THE POSSIBLE VALUES OF THE STRAIN INVARIANTS FOR ISOCHORIC DEFORMATIONS

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by

KENNETH N. SAWYERS

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On the Possible Values of the Strain Invariants for Isochoric Deformations

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Abstract

A description is given of all possible values of the strain invariants (I_1 and I_2) that may be attained in any experiment involving isochoric deformations and a graphical representation of the eigenvalues of the strain matrix is derived for any specified values of the invariants.

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1. Introduction

The eigenvalues of the Cauchy strain matrix $\underset{\sim}{C}$, for an isochoric deformation, are the roots of

$$\mu^3 - I_1\mu^2 + I_2\mu - 1 = 0 , \tag{1.1}$$

where

$$I_1 = \mathrm{tr}\, \underset{\sim}{C} , \quad I_2 = \tfrac{1}{2}\{(\mathrm{tr}\, \underset{\sim}{C})^2 - \mathrm{tr}\, \underset{\sim}{C}^2\} . \tag{1.2}$$

Physically, the roots are the squares of the principal extension ratios. Denoting them by α, β and γ, we have

$$\alpha\beta\gamma = 1 \tag{1.3}$$

and, for example,

$$I_1 = \alpha + \beta + (\alpha\beta)^{-1} , \quad I_2 = \alpha^{-1} + \beta^{-1} + \alpha\beta . \tag{1.4}$$

That the strain-energy function for an isotropic incompressible elastic material depends on $\underset{\sim}{C}$ through I_1 and I_2 was apparently first exploited in a systematic way by Rivlin and Saunders [1] who devised experiments wherein these invariants could be controlled independently. After plotting expressions equivalent to (1.4) for (all) positive α and β, Hart-Smith [2] pointed out that only certain values of I_1 and I_2 could be achieved in any (isochoric) experiment. This also may be deduced analytically by writing down the restrictions on I_1 and I_2 which ensure that (1.1) has three real and positive roots. Thus,

$$4(I_1^3 + I_2^3) - I_1^2 I_2^2 - 18\, I_1 I_2 + 27 \leq 0 \tag{1.5}$$

and, following Carroll [3],

$$3 \leq I_1 < \infty \quad \text{and} \quad 3 \leq I_2 < \infty \ . \tag{1.6}$$

In this note we give a geometrical interpretation of (1.5) and (1.6) and obtain a graphical representation of the roots of (1.1) for specified values of the invariants. The analysis is based on the observation that (1.1) defines a one-parameter family of straight lines in the $I_1 I_2$-plane, μ being the parameter, which is described as μ assumes all positive values. In part, this work can be regarded as a special case of a problem considered by Rösel [4] who determined the possible values of the principal invariants of symmetric second-order tensors in three dimensions.

2. The analysis

We note that μ is a root of (1.1) if and only if I_1 and I_2 are related by

$$I_2 = \mu I_1 - \mu^2 + 1/\mu \quad , \tag{2.1}$$

which is a straight line in the I_1I_2-plane. Let L_μ denote this line. It is readily verified that μ is a root of (1.1) for all points (I_1,I_2) on L_μ. The slope of L_μ is

$$dI_2/dI_1 = \mu \quad . \tag{2.2}$$

The equation of the envelope of the family of lines follows from the requirement that μ be (at least) a double root of (1.1) (see, for example, [5]). This yields the parametric expressions

$$I_1 = 2\mu + 1/\mu^2 \ , \quad I_2 = \mu^2 + 2/\mu \ , \quad 0 < \mu < \infty \tag{2.3}$$

which are plotted in Fig.1. The envelope consists of two smooth arcs which meet in a cusp at the point $(I_1,I_2) = (3,3)$ and which lie entirely within the quadrant of the I_1I_2-plane defined by (1.6). The lower arc has negative curvature and is described as μ increases from zero to unity. The upper arc has positive curvature and is described as μ increases from unity. These arcs are tangent to the line $I_2 = I_1$ (i.e., L_1) at the point (3,3).

Any specified values of I_1 and I_2 , i_1 and i_2 , say, are conveniently represented by the single point (i_1,i_2) in the I_1I_2-plane. Referring to Fig.1, it is seen to be possible to draw three distinct straight lines through (i_1,i_2), and tangent to the envelope, if and only if this point lies above the lower arc and below the upper arc. Each of these lines is a member of the family defined by (1.1) and, thus, corresponds to some definite positive value of μ . From the geometrical significance of the envelope, we conclude that (1.1) has three distinct positive roots when $I_1 = i_1$ and $I_2 = i_2$ if and only if (i_1,i_2) lies above the lower arc and below the upper arc.

Through such a point as described above, it is possible to draw one line tangent to the lower arc, another tangent to the upper arc, and the third tangent to the lower or upper arc accordingly as (i_1,i_2) lies below or above L_1 . Whence, one eigenvalue of $\underset{\sim}{C}$ is always less than unity, another always greater than unity, and the third is less than or greater than unity if (i_1,i_2) is below or above L_1 , respectively. From (2.2) we see that the numerical values of α,β and γ can be determined by measuring the slopes of L_α , L_β and L_γ , respectively*. While this procedure may not yield the highest accuracy, it does afford a means of visualizing how the eigenvalues depend on I_1 and I_2 if these invariants were to be varied in some way.

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* These can also be found, of course, by employing the well-known equations for the roots of a cubic.

For example, α is constant if I_1 and I_2 were both to change in such a manner that the point (I_1,I_2) moves along the line L_α. We note that L_α intersects the envelope at the point

$$(I_1,I_2) = (\alpha+2/\alpha^{\frac{1}{2}} , 2\alpha^{\frac{1}{2}}+1/\alpha) \quad . \tag{2.4}$$

An implicit description of the region "inside" the arcs of the envelope is given by (1.5) and (1.6) where strict inequalities are taken. The envelope itself, given by (2.3) or by the equality in (1.5), with (1.6), is the trace of one branch of the surface, drawn by Rösel [4], in the plane corresponding to $\det \underset{\sim}{C} = 1$.

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Figure Caption

Fig.1. The envelope of the family defined by Eqn.(1.1).

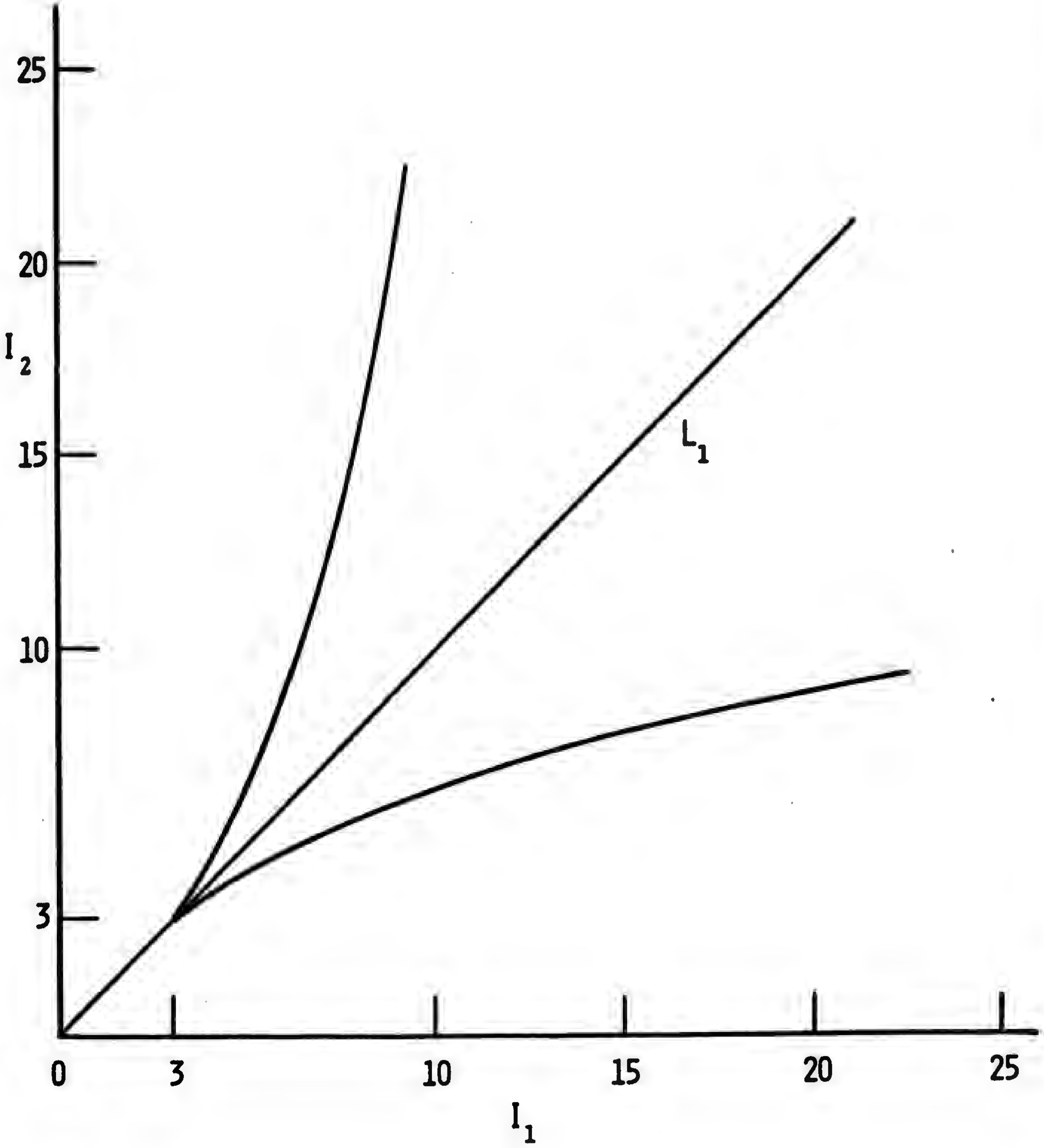

FIGURE 1.

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