

Electrodynamics of Moving Media

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On the basis of the Minkowski formulation, the total energy-momentum tensor of a system consisting of matter and electromagnetic fields is derived from the macroscopic theory. The analysis of this tensor shows that the electromagnetic fields supply the matter with momentum and energy. Consequently, the electromagnetic part and the material part overlap each other in the total energy-momentum tensor. Hence it is impossible to divide the total energy-momentum tensor into an electromagnetic tensor and a material tensor.

In a closed system, in general, only the total energy-momentum tensor has physical significance and can be defined.

Further, the generalized force which acts on the matter is obtained and interpreted clearly.

I. Introduction

Electrodynamics of moving media has been discussed by a large number of investigators for long years, and until the present many different forms of an electromagnetic energy-momentum tensor within media have been put forward^{1–4}. However, no form is universally accepted, although Minkowski's tensor is the most well-known and widely used of them⁵.

The present paper develops Møller's theory of an elastic body⁶ and analyzes, on the basis of the Minkowski formulation, a system consisting of matter and electromagnetic fields. The effect of the electromagnetic fields on the matter is revealed. Further, the generalized force which acts on the matter is obtained and interpreted clearly.

For the sake of simplicity, only isotropic and nondispersive media with linear constitutive relations are considered. Further, the summation convention is used. The Latin subscripts assume the values 1, 2, 3, 4, whereas the Greek subscripts assume the values 1, 2, 3.

II. The Lorentz Force, the Joule Heat, and the Electrostriction and Magnetostriction Forces

In the first place, the force per unit volume that acts on stationary media in stationary electromagnetic fields is considered. If the elastic force is left out of consideration, it is given by^{7, 8}

$$\mathbf{f}_{\text{ext}} = \rho \mathbf{E} + \mathbf{J} \times \mathbf{B} - \frac{1}{2} E^2 \text{grad } \epsilon - \frac{1}{2} H^2 \text{grad } \mu + \text{div } \mathbf{T}, \quad (1)$$

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where ρ and \mathbf{J} are the true charge and current densities. The last term in (1) is the vector whose components are

$$(\text{div } \mathbf{T})_\alpha = \partial \sigma_{\alpha\beta} / \partial x_\beta, \quad (2)$$

where

$$\sigma_{\alpha\beta} = -\frac{1}{2} \alpha_1 E_\alpha E_\beta - \frac{1}{2} \alpha_2 E^2 \delta_{\alpha\beta} - \frac{1}{2} b_1 H_\alpha H_\beta - \frac{1}{2} b_2 H^2 \delta_{\alpha\beta}; \quad (3)$$

the Kronecker symbol is denoted by $\delta_{\alpha\beta}$. The coefficients α_1 and α_2 in (3) represent the rate of change due to the strains of the permittivity ϵ of the medium, whereas b_1 and b_2 represent that of the permeability μ .

Note that the last term in (1) is quite different from the other terms in nature. It represents the electrostriction and magnetostriction forces; these act as surface forces, because $\sigma_{\alpha\beta}$ represents the internal stresses which occur to evoke the strains. In contrast with it, the first four terms in (1) represent the Lorentz force, which acts as a volume force.

Even in the general case of time-dependent fields, only the Lorentz force and the electrostriction and magnetostriction forces act immediately on the medium. Moreover if the fields do not vary rapidly, it may be assumed that the Lorentz force and the electrostriction and magnetostriction forces are represented by (1). The generalized force is discussed in detail in Section VI.

Next the case in which media are moving with a constant velocity \mathbf{v} is considered. The following identity is generated from Minkowski's field equations by the tensor manipulation⁹:

$$f_i^* = -\partial S_{ik} / \partial x_k, \quad (4)$$

where

$$f_i^* = F_{ij} J_j + \frac{1}{4} \left(F_{kl} \frac{\partial H_{kl}}{\partial x_i} - \frac{\partial F_{kl}}{\partial x_l} H_{ik} \right), \quad (5)$$

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