Current Bearing Anti-Force Waves (Lightning Return Stroke)

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In our investigation of breakdown waves, we apply a one-dimensional, steady-state, three-component fluid model. The electrons are assumed to be the main element in propagation of the wave and the wave is considered to be shock fronted. Our set of electron fluid dynamical equations is composed of the equation of mass flux, equation of conservation of momentum, equation of conservation of energy, plus Poison's equation. For lightning return strokes, experimentally, few much larger than usual currents have been reported [1]; we intend to examine existence of such large currents; also, for return strokes, some researchers have suggested existence of a relationship between the peak current and wave speed values [2], we intend to find out its validity as well.

1. Model, Solution and Results

Anti-force waves are breakdown waves for which the electric field force on electrons is in the opposite direction of the wave propagation; however, the electron gas temperature is assumed to be large enough to sustain the wave motion. Following the shock front, there is a thin dynamical transition region referred to as the sheath region of the wave; where, the electric field starting with its maximum value at the shock front reduces to zero at the end of the sheath region, and the electrons, starting with an initial speed at the wave front, slow down to speeds comparable to those of heavy particles. For theoretical investigation of anti-force waves with a large current behind the shock front, we will use Hemmati et al.'s [3] modified set of electron fluid dynamical equations and the boundary condition on electron temperature at the shock front. In dimensionless variables, the equations are

$$\frac{d}{d\xi}[\nu\psi] = \kappa\mu\nu, \tag{1}$$

$$\frac{d}{d\xi}[\nu\psi(\psi-1) + \alpha\nu\theta] = \nu\eta - \kappa\nu(\psi-1), \tag{2}$$

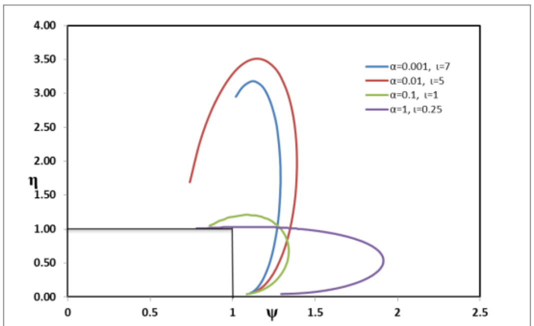
$$\frac{d}{d\xi}[\nu\psi(\psi-1)^2 + \alpha\nu\theta(5\psi-2) + \alpha\nu\psi - \frac{5\alpha^2\nu\theta}{\kappa}\frac{d\theta}{d\xi} + \alpha\eta^2] = 2\eta\kappa\iota\alpha - \omega\kappa\nu[3\alpha\theta + (\psi-1)^2], \tag{3}$$

$$\frac{d\eta}{d\xi} = \kappa\iota - \frac{\iota}{\alpha}(\psi-1) \tag{4}$$

$$\theta_1 = \frac{\psi_1(1-\psi_1)}{\alpha} - \frac{\kappa\iota}{\nu_1}. \tag{5}$$

Where ν, ψ, θ represent non-dimensional electron number density, velocity and temperature; η, μ, ξ, ι, represent net electric field, ionization rate, position within the sheath region and current at the shock front; κ and α are wave parameters.

For lightning return strokes, experimental current values measured are generally in the 5-30 kA range; however, some, for example Rakov [1], has reported the highest recorded peak currents in Japan to be 280, 320 and 340 kA. Our dimensionless current, $\iota = 1$, represents an actual current value of 10 kA. We use a trial-and-error method to integrate equations 1-4 through the sheath region of the wave. Our solutions for a range of wave speeds, and also maximum current values possible for those wave speeds, meet the expected conditions at the trailing edge of the wave $(\psi_2 \rightarrow 1; \eta_2 \rightarrow 0)$. The following is a graph of the net electric field as a function of wave speed within the sheath region of the wave.



Electric field, η, as a function of electron velocity, ψ, for dimensionless wave speed, α, and current, ι, values of 0.001, 7; 0.01, 5; 0.1, 1 and 1, 0.25 within the sheath

For return strokes, in addition to existence of large currents, we also confirm existence of a relationship between the wave speed and peak current values.

2. References

[1] V.A. Rakov. 25th Int. Conference on Lightning Protection. (2000). 103-108.

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[3] M. Hemmati, W.P. Childs, H. Shojaei and D.C. Waters. 28th International Symposium on Shock Waves, 2011, England.