J. Phys. A: Math. Gen., Vol. 10, No. 2, 1977. Printed in Great Britain. © 1977

An approach to the understanding of inertia from the physics of the experimental method

R C Jennison and A J Drinkwater
The Electronics Laboratories, The University, Canterbury, Kent CT2 7NT, UK

Received 3 August 1976, in final form 13 October 1976

Abstract. Current theories of the origin of inertia are reviewed. An alternative treatment is given. This recognizes the physical extent of even the smallest masses and the interaction effects of physical measurement. It is shown that there are very good physical reasons for identifying the origin of inertia with the local system and that this simultaneously accounts for quantization and the units of length and time. Two experiments are described which illustrate some of the properties under discussion.

1. Introduction

This account will be concerned primarily with the origin of inertia, that is the reluctance of a body to change its state of uniform motion, and will contain a brief description of experiments specifically designed to illustrate certain aspects of the theme.

It is remarkable that no viable alternative to Ernst Mach's principle of inertia (Mach 1908) has been propounded, yet there have to be good physical reasons why bodies continue in the same state of motion and why the act of acceleration produces any force at all, let alone a specific force. Mach's principle ascribes inertia to the environment formed by the distant masses in the universe. It does not directly produce the precise quantitative relation $F = ma$, relating a specific force to a specific quantity of mass by means of an acceleration measured in an unspecified frame which, to Newton, was almost certainly the local, or proper, frame of the mass. Mach simply implies that, because of the apparent symmetry in the kinematics, this force must somehow be produced, and thereby somehow have the correct magnitude, as a result of the relative motion of the rest of the universe. Since Mach's time, estimates of the size and mass of the universe have changed by orders of magnitude but, in the absence of a quantitative relationship, Newton's laws have remained impervious to these changes. For a Machian interpretation of inertia to be valid, the opposition to a change in motion has to be instantaneous and cannot be communicated to and from distant space at the speed of light—a process which would involve a delay time of about 3×10^{10} years between action and reaction. Mach did not stipulate how to overcome this problem but he was, in later years, an outspoken opponent of relativity and he may not have been concerned.

Mach's original thesis shows a number of fallacies in both logic and physics. For example: 'When we reflect that we cannot abolish the isolated bodies . . . it will be found expedient provisionally to regard all motion as determined by these bodies'. One cannot abolish a wealth of parameters in almost every physical problem but inability to abolish does not necessarily identify the criminal. Nevertheless the root of Mach's problem may be traced to a misconception in physics. Although many of his contemporaries were aware that mass and spatial extent are inseparable, Mach, and, unfortunately, some of his later disciples, postulated hypothetical coordinate systems in which it was assumed that masses could be represented always by points even when the systems were accelerated. If this were so then one could be driven on the grounds of symmetry and lack of local causation to a Machian or even a magical explanation of inertia to account for the physics of the situation, but it is clearly not so and as soon as one recognizes that all mass, even on the scale of the fundamental particles, has a finite extent a simple physical explanation of inertia is possible.

Sciama (1953) overcame some of the objections to Mach's principle by postulating that, in the rest frame of any body, the gravitational field of the universe as a whole cancels the gravitational field of local matter. He then claimed that, in his theory, the inertial effects arise from the gravitational field of a moving universe. Sciama claimed that his theory differed from general relativity in a number of respects but Davidson (1957) showed that the two could be consistent and emphasized the fitness of the steady-state theory as a cosmological solution which permits this possibility.

We agree with Sciama that the problem of motion can be completely discussed in terms of observables but we would question his limited interpretation of physical observables. Following Mach, he goes on to claim that 'kinematically equivalent motions must be dynamically equivalent'. There seems to us to be no foundation whatsoever for this conclusion if one is discussing not simply a mathematical model of representative mass points but a real universe in which all particles of mass are finite in spatial extent. One can also quote innumerable trivial examples where the statement in this form is extremely dubious. Kinematically a car accelerates relative to a 'stationary' balloon. The measurement of the acceleration of the car from the balloon or the balloon from the car are both legitimate observations, which are kinematically equivalent and may be compared with considerable accuracy (there will be an extremely small asymmetry in the clock rates although this is not apparent from Mach's or Sciama's argument), but it is the car and not the balloon which experiences the effects of acceleration when the throttle is opened or when it crashes into an obstacle. This argument can be countered by claiming that some quantities are more equivalent than others and that the balloon is just part of the rest of the universe. One would therefore not expect to observe a reciprocal dynamic effect unless one could get rid of the rest of the universe and this one is not permitted to do. The physics of the argument becomes somewhat tenuous although Sciama, Davidson and others have valiantly tried to develop it under a cloak of impeccable mathematics. We find Sciama's example of the Foucault pendulum as an example of a dynamic experiment to be perfectly consistent with the propagation of light in the flat space on which he bases his thesis and its motion relative to light rays which also coincide with the fixed stars is fully consistent with our own analysis. What would be impressive would be if the Foucault pendulum did *not* align with the local null geodesics!

The fact that distant stars remain in fixed positions when observed from inertial frames does not require a dynamical relationship between distant and local matter. This has been well discussed by McCrea (1971).

Finally we note that Mach's principle does not account for the quantization of momentum but experiments show that inertial changes involving mass are always quantized.

2. An alternative approach

Our discussion in this paper will concern the dynamics and other aspects of physics which are applicable where energy is bounded in small regions of space.

We will accept that, in a universe that is completely empty apart from two minute observers, the path of a ray of light to an observer who is not accelerated will be a straight line. This follows from Einstein's original treatment and it may be shown that it is also experimentally inevitable. We will further accept that in any vacuous region of the universe the velocity of light c is locally invariant and $c = \nu\lambda$ where ν and λ respectively denote the frequency and wavelength of an electromagnetic wave.

Consider two small masses in close proximity in an otherwise empty universe. These masses must, of necessity, have physical extent and the behaviour of a distributed mass under accelerated motion cannot be reduced to the behaviour of a hypothetical point mass because of the phase lags introduced by the finite speed of light. We take two masses in order to establish the kinematics but we will develop our argument to show that a single illuminated mass or a mass with a small leakage of electromagnetic energy is sufficient to establish the dynamics.

Self-gravitational and inter-gravitational forces on the two very small masses are typically more than fifty orders of magnitude smaller than the inertial forces which we shall consider and they do not, therefore, enter the first-order theory that we present. Sciama specifically ignored the effects of electromagnetism but we shall equally specifically centre our attention on these effects.

We are at liberty to form the masses in any way that we please. We therefore choose phase-locked cavities. These shall be resonant cavities filled with monochromatic radiation contained against the radiation pressure by arranging an electrostatic field to provide an attraction between the perfectly reflecting walls. The analogue of a parallel-plate capacitance of area very much greater than the square of wavelength, will suffice for much of this discussion. The mass of the container is not relevant to the discussion and will be assumed to be vanishingly small.

We now either open a small pinhole in the wall of one of the cavities thereby letting out an electromagnetic signal or, otherwise, we allow the universe to contain one ray of light which may fall on one of the masses. In either case, according to the laws of electromagnetism, we would expect the mass to move, whatever movement may mean. We have introduced the second mass to establish the kinematics and therefore we can say, at least, that it moves relative to the second mass; but we shall see that this second mass plays little or no part in the dynamics of the subsequent motion.

We comment on the legitimacy of employing weak electromagnetic waves to instigate the motion by pointing out that physical measurements have no meaning unless information can be conveyed to the observer. The transmission and reception of this information involves the laws of electromagnetism and we see no reason to discard these laws in the framework of the present problem. If the laws are discarded then it seems to us that measurements can no longer be made and the physics of the problem has no meaning.

We may also consider the same elementary masses moving towards each other along parallel axes so close that the particles collide obliquely and adhere. It is then easy to show that their state of motion becomes rotational relative to the axis of the original parallel trajectories but it can be shown from an extension of the discussion in this paper that the physical conditions are different in the two states. Because the masses cannot be reduced to points there is an asymmetry of distribution of the internal energy (and hence a force) in the rotating state but not in the state of uniform translation. There is no coupling between the masses and any other masses nor is there even need to observe a non-rotating axis in order to establish and detect this state of rotation.

3. A simple analysis

Consider radiation trapped between conducting sheets. The surface area of the sheets may be very large so that leakage may be neglected and, over the time scale of interest, the internal energy is invariant. It has been shown in standard texts on electromagnetism that the radiation produces a static force on the boundary. For plane waves, this force pulsates at twice the wave frequency but the mean value over any half period is given by $\bar{F}=E/L$ where E is the total energy in the wave system and L is the total length containing the energy E. $\bar{F}$ depends only on the definition that energy equals force times distance and does not depend on the laws of inertia. The formula may be obtained either from the energy integral or from the Poynting vector of the electromagnetic field. If the radiation is circularly polarized a constant force may be obtained in place of the pulsating component. Now set up an electrostatic field on the sheets so that they mutually attract with a force equal to that of the radiation. The system now will be in static equilibrium.

4. The effect of movement on a phase-locked system

We now consider what happens if we try to move an untethered halfwave system, of the type just described, in a direction parallel to the internal axis of propagation. Movement of the perfectly reflecting wall of the cavity into the radiation falling upon it from the internal waves will create a small excess force from the radiation for it will appear Doppler shifted to the blue and the rate of energy flow is increased relative to the equilibrium value when the wall was at rest (Einstein 1905). Thus one of Newton's laws appears naturally at this stage, an equal and opposite reaction is set up in opposition to the impressed force, indeed the two are inseparable, the impressed force only exists because of the reaction to the new velocity.

The wall remains stationary in its own frame, so we may derive the excess force $\overline{\delta F}$ by considering the change in the available energy flowing into the wall; this we obtain from Einstein's discussion of the energy of a light complex. Einstein, in his paper on the electrodynamics of moving bodies, showed that, for a moving observer, the energy of a light complex in classical electromagnetic wave theory, changes according to the relationship

$$\frac{E'}{E}=\frac{1-v/c}{(1-v^2/c^2)^{1/2}}.$$

This relationship is of the same form as the relativistic Doppler relationship and it is of interest to quote Einstein's comment: 'It is remarkable that the energy of and frequency of a light complex vary with the state of motion of the observer in accordance with the same law'. Thus the excess force is *velocity* dependent and does not utilize Newton's law of acceleration. Hence, in the frame of the wall:

$$\overline{\delta F}=\frac{E}{L'}\frac{1\pm\overline{\delta v}/c}{(1-\overline{\delta v}^2/c^2)^{1/2}}-\frac{E}{L} \tag{1}$$

where $\overline{\delta v}$ is the mean velocity of the wall during the time that the radiation into which it is moving is that from the original rest state. The first term is similar in form to the Doppler shift (Einstein 1905) but the second-order component has negligible effect on this analysis and will be omitted for clarity (see the discussion after equation (4)). The choice of sign depends upon whether the wall is pushed or pulled. The second term is the restoring force which remains unchanged in the proper frame when the wall is moved. Thus to first order:

$$\overline{\delta F} = \pm \frac{E}{L} \frac{\overline{\delta v}}{c}. \tag{2}$$

This relation applies from the moment, t_0, that the wall starts to move, for the whole of the time that the wall is moving into the original radiation in the cavity. After a certain time, δt, however the radiation that has left the moving wall will reach the far end of the cavity and exert an excess pressure on this far end, causing it to move, and then return to the original motive wall. Precisely at this instant, $t_1 = t_0 + \delta t$, a new stable state of motion is reached, the up-dated radiation returns and the wall latches on to the nodal position associated with this regenerated radiation. If the motive force is immediately removed at t_1, an external observer associated with the original frame, Σ_0, occupied by the system before t_0 will find that the whole system must continue to move forever at the velocity $2\delta v$ as a result of the continual regeneration of the internal waves in the cavity at a frequency and an energy which, to him, differs from that associated with the system before t_0. An observer with the cavity, on the other hand, will not be able to determine any change in his system. If he measures the length by means of light signals, these signals will be affected in exactly the same way as the internal radiation in the cavity and its length will not have changed. Similarly, to his own clock, the internal frequency will not have changed and the internal energy trapped within the system will, to him, remain constant. It is possible to identify a new frame, Σ_1, with the cavity in this state and relative to this frame the original frame Σ_0, is moving at a velocity $-2\delta v$. We may now start the process all over again and provide a motive force at the wall for a sufficiently long time for the radiation once again to traverse the whole length of the cavity and return to the first wall. Stopping the motive force again at this point enables the system to coast in a frame Σ_2, travelling at $2\delta v$ relative to Σ_1 and $4\delta v$ relative to Σ_0. Again, however, no change will be observed in the frame Σ_2. The same process may be repeated indefinitely and without pausing as each new frame is attained but the effect is to achieve a quantized 'staircase' of velocity relative to Σ_0 whilst retaining invariant physical parameters in the frame Σ_i occupied by the system at any epoch, t_i.

5. The velocity staircase

The staircase of velocity relative to Σ_0 is shown in figure 1, the theory behind it is elegantly simple and can be modelled on an analogue computer. When the wall is pushed with velocity δv into the initially latent radiation of frequency ν, it transmits a step function of radiation of frequency $\nu(1+2\delta v/c)$ towards the far end (the factor of two results from the reflection). This step function ultimately reaches the far end where the wall endeavours to maintain the original state in its own frame in order to remain in local equilibrium. It therefore moves at $2\delta v$ relative to Σ_0 and the radiation returns from it at a frequency $\nu(1-2\delta v/c)$ relative to Σ_0. This lower-frequency radiation is

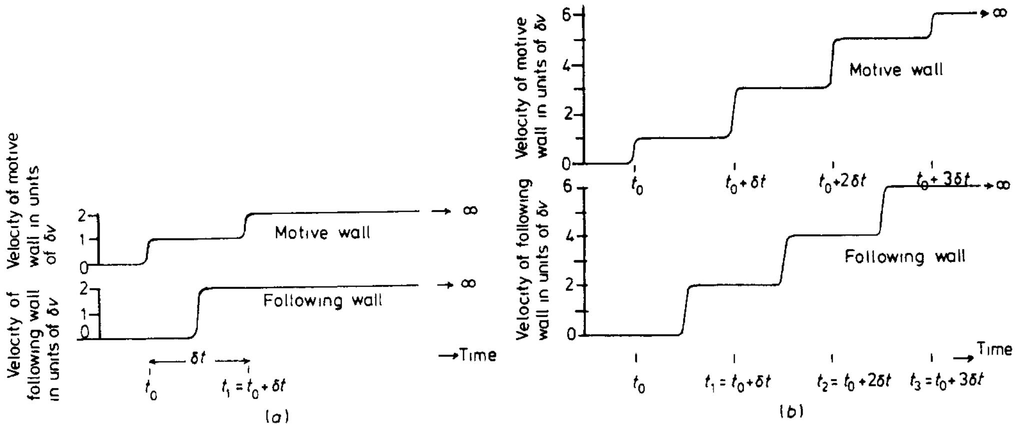

Figure 1. (*a*) The effect of maintaining a constant motive force for precisely the interval, δt, taken by the radiation to complete one round trip in the cavity. The cavity continues to move forward at a velocity $2\delta v$. (*b*) The staircase of velocity produced by a motive force maintained constant for a time $3\delta t$. In the limit, for a very large number of steps, the staircase approximates to classical linear acceleration.

less energetic than the latent radiation, so that when it reaches the original motive wall it provides a relief of pressure precisely equivalent to that of the original push and a new equilibrium state is attained. The whole system must therefore continue to move forward at velocity $2\delta v$ if the original motive force is now removed. If the motive force is continued at the same value then the system will continue to rise up the velocity staircase until ultimately it coasts at the last complete 'quantized' state attained when the force is removed.

We will not, in this account, deal with the interesting circumstance which occurs when the applied force lasts for a non-integral number of steps of the staircase. It is of interest, however, to note that if the motive force is provided by interaction with an external electromagnetic field, then, by reciprocity, the energy absorbed in an incomplete step may be radiated back into the external field which gave rise to the motion and the system will coast at the last complete velocity step when the external field is switched off.

The velocity staircase clearly represents an acceleration despite the fact that each step is velocity dependent. The quantization of the velocity is, of course, dependent on the wavelength of the internal radiation and does not, in this general case, correspond to Planck's quantum of action (see the section on gating of momentum). The law of motion may be obtained from figure 1 and equation (2) by replacing the length L by its equivalent form $\frac{1}{2}c\delta t$. Hence for n steps

$$\overline{\delta F} = \frac{E}{\frac{1}{2}c\delta t n}\,\frac{n\overline{\delta v}}{c} = \frac{E}{c^2}\,\frac{2\overline{\delta v}}{\delta t}. \tag{3}$$

Prior to Newton, the Galilean relationships enable us to identify the term $2\overline{\delta v}/\delta t$ with an acceleration, a. Hence

$$\overline{\delta F} = \frac{E}{c^2}a. \tag{4}$$

But Newton found by observation that

$$F = ma,$$

whence we now identify E/c^2 with a rest mass, commensurate with Einstein (1905). Thus we derive Newton's law in a step-like or 'quantized' form in the proper frame together with a proper mass and Einstein's mass–energy relation $E = mc^2$ from this simple mechanism. It is remarkable that equation (4) is acceleration dependent whereas the basic internal phenomenon is velocity dependent, in common with the Doppler shift. Since $2\overline{\delta v}$ is only an *incremental* or differential velocity gained in a very short interval δt, the error in Newton's law in the *proper* frame, resulting from the exclusion of second-order terms, is extremely small. For example, if we choose a cavity with $\delta t = \lambda_C/2c$, where λ_C is the Compton wavelength, the differential velocity $\overline{\delta v}$ within the system becomes relativistic to the extent of producing only a 1% error in $\overline{\delta F}$ in equation (3) when the acceleration $2\overline{\delta v}/\delta t$ is greater than 10^{27} *g*.

Another of Newton's laws also assumes a natural explanation. As soon as a system gains one of the quantized self-regenerative states of equilibrium, it must continue in that state until it receives a subsequent force for a sufficient time to change it to another quantized self-regenerative state.

6. The gating of momentum

Consider the application of an external electromagnetic field to the outside of a cavity wall. The field cannot appear instantaneously but will have a leading edge which is frequency dependent. The higher the frequency of the external wave impinging on the boundary, the more rapid will be the change in the force exerted by its Poynting vector on that boundary.

If the boundary conditions are similar on either side of the boundary wall then, in order that the wall may remain in equilibrium, the increase in the energy flow onto one of its surfaces due to the arrival of the external wave must equal the increase in the energy flow on its opposite surface due to the increment resulting from its motion into the trapped electromagnetic wave. Hence, because of the remarkable symmetry between the transformations for energy and frequency commented on by Einstein in his 1905 paper, the excess of the Doppler frequency above the rest frequency, ν_0, on the inner side of the wall must be equal to the external wave frequency, ν_a, on the outside of the wall. Whence,

$$\nu_a = \nu_0 \frac{\overline{\delta v}}{c}$$

and therefore,

$$\overline{\delta v} = \frac{\nu_a}{\nu_0} c.$$

Multiplying both sides by $2m_0$, we obtain the momentum, *p*, gained in achieving the final increment of velocity $\overline{2\delta v}$ corresponding to a new self-regenerative stable state

$$p = m_0 \overline{2\delta v} = 2m_0 c \frac{\nu_a}{\nu_0} = \left(\frac{2m_0 c}{\nu_0}\right) \nu_a. \tag{5}$$

The expression in large parentheses is a proper constant of the cavity system at rest in any frame. Putting $c(2m_0c/\nu_0) = K$, we have

$$p = \frac{2m_0c^2}{\nu_0}\frac{\nu_a}{c} = K\frac{\nu_a}{c}.$$

For a man-made cavity the value of K will depend upon the ratio of the intensity to the frequency of the trapped wave. In naturally formed particles it appears, however, that there may be a direct relationship between the intensity and the frequency for trapping to take place.

Noting that in the process of electron–positron pair production, stable particles having a rest mass are produced from an electromagnetic wave having none, we may examine what happens if we substitute the experimentally observed threshold frequency for pair production in place of ν_0 and the experimentally determined electron mass in place of m_0. We then find that the constant in large parentheses has the value $2{\cdot}2\times10^{-42}$ m kg, whence, in order to reach the next self-regenerative equilibrium state for our model, the momentum

$$p = \overline{2\delta v m_o} = 2{\cdot}2\times10^{-42}\nu_a \text{ m kg s}^{-1}.$$

Thus, there is a particular frequency at which it is observed that electromagnetic radiation can be trapped by a natural process and localized in free space to form particles having rest mass. Our model predicts that the particles will interact with radiation in a step-like or quantized manner and acquire precise increments or 'quanta' of momentum proportional to the applied frequency. For the specific internal frequency trapped in pair production, the constant of proportionality when multiplied by the velocity of light, c, gives $K = h = 6{\cdot}6\times10^{-34}$ J s.

Similarly, we may also derive $E_a = h\nu_a$ where E_a is the energy acquired by the particle.

7. Rigid rods and the units of length and time

In order that physical measurements should have meaning it is necessary that the basic unit of length should be capable of transference between systems. It must be possible to move it and it must retain its unit properties in the frame to which it is moved. Thus 'rigid' rods might fall into three categories, only one of which could be meaningful, for the rod must have its counterpart in the real world in order that the world picture derived from it represents the world as it is.

(*a*) The rod would offer infinite resistance and would not move even if the available energy were also infinite. This applies to the Newtonian rigid rod ($c = \infty$ internally) whether or not Mach's principle is applied.

(*b*) It would offer no resistance and no force or energy need be supplied. This category refers to an empty system and has no physical significance in the real world.

(*c*) It would offer a specific resistance, requiring a specific force to give it a specific acceleration and a specific amount of energy to give it a specific velocity, commensurate with the laws of inertia.

The mechanism that we have discussed in this paper is at present unique in that it falls into category (*c*). A lossless standing wave must always retain its proper length, for if proper measurements of its length could be made by using light signals from the node they would be subject to the same phenomena as the internal radiation and the operational length would be found to be invariant. As no strain may be *measured* the system has an effective Young's modulus of infinity.

The unit of length requires the property of rigidity combined with an invariant calibration. If the invariant calibration is the local wavelength for pair production, as predicted by relating this to our general model, the unit will be maintained under all circumstances in all parts of the universe.

The unit of time follows from the unit of length as the periodicity of the internal wave. The units of length and time in this system are inseparably united in the proper relation $c = \nu\lambda$. The simple mechanism of this proper clock is interesting and fundamental: the system continuously regenerates the internal signal so that it is perfectly carried forward from one cycle to the next. It is the perfect pendulum.

An interesting result of this definition is that not only the clock to measure time but also meaningful time itself (rather than merely an unscaled dimension) can only exist where matter exists in the manner defined. Thus if matter is annihilated and transformed into radiation, the clock stops on annihilation and starts again from zero if a standing wave system, and thence matter, is created out of the radiation.

8. Experimental verification

Some aspects of this work are already adequately confirmed by experiment. For example, the formation of electron pairs from γ rays, the quantum theory, Newton's laws and Einstein's relation, $E = mc^2$. The theory also predicts a relationship between inertia, rigidity and the units of length and time. Certainly electrons and protons are always observed to obey the rules of proper length and proper time but our theory goes further and predicts that, as the fundamental phase-locked cavities of the universe, they are responsible for the fundamental basic units of these parameters in the physical world. Their dimensions ultimately dictate the magnitude of the interactions of all macroscopic bodies.

We have found that a considerable aid to discussion of our ideas could be achieved by constructing a macroscopic model of a one-dimensional form of a stable 'particle' consisting of trapped radiation. Any radiation trapped in a cavity-like configuration should respond inertially in the manner suggested, in contradistinction to the remote hypothesis of Mach. The problem is to amplify the effect so that it may be observed in a macroscopic system with relatively weak long-wave radiation and, to this end, sensors and control systems were used to enhance the boundary conditions. Two models have been constructed in our laboratories. Their main virtue is in demonstrating the non-trivial property of the preservation of a proper unit of length in the acceleration phase between different velocity states. The second model also has the property of inertia. Each of these models will now be described briefly.

9. The servoed optical etalon

A Michelson-type optical interferometer using a helium–neon light source was constructed and is shown in figure 2. The mirrors terminating the two limbs of the interferometer were mounted on moving-coil transducers having a range of movement

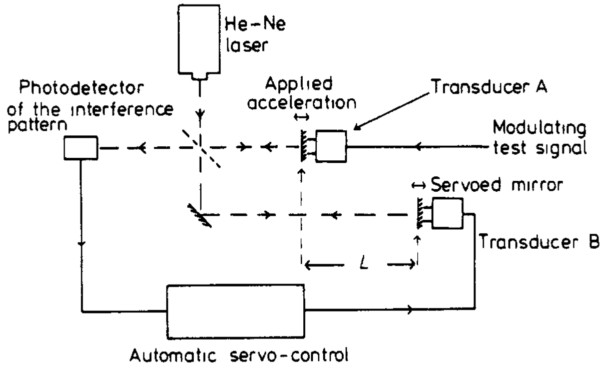

Figure 2. The servoed optical etalon. The length L is maintained constant under acceleration by servo-control applied to transducer B.

of about 1 cm. One of these mirrors could be accelerated over the full range of movement by the application of a signal from a generator whilst the other mirror was placed at a nominal path difference of about 100 000 λ and servo-controlled from the interference pattern so as to maintain the same state of interference irrespective of the state of motion of the driven reference mirror. Accelerations of up to 1 g were applied to the driven mirror and it was found that the servoed following mirror maintained a constant wavelength difference within the observational limit under all circumstances, thus preserving the same optical length and simulating a rigid system.

This technique should have many useful applications for the precise location of objects in general applied physics.

10. The freely floating phase-locked cavity

A closer analogue to the required conditions could be formed at longer wavelengths and an unusual etalon was therefore constructed (see figure 3) using a 3 cm (microwave) Gunn diode as a local source of the internal radiation. The etalon was leaky but the internal energy was continuously replenished from the Gunn diode which was effectively integral with one of the walls so that the system had much in common with the required cavity. The Gunn diode fed a short horn from which the radiation propagated through free space to a concave conducting surface which reflected much of the radiation back into the horn. The concave conductor had a very small loop located in a hole at its centre to sample the magnetic component of the electromagnetic field. The loop was connected to a diode crystal detector. The concave conductor was mounted on the cone of a small loudspeaker so that it could be continuously vibrated at audio frequencies with an excursion of about 100 μm. The loudspeaker with its reflector, loop and diode were mounted on a small trolley free to run on parallel rails. The Gunn diode with its horn was mounted on a similar trolley running on the same parallel rails. A second small loop and crystal diode to sample the magnetic component of the electromagnetic field was mounted in the wall of the horn. Each trolley was equipped with a small motor and each was independently servo-controlled to a node of the 3 cm electromagnetic field by phase-sensitively detecting the audio frequency signal providing the small vibration to the mirror. This technique ensured that each end of the

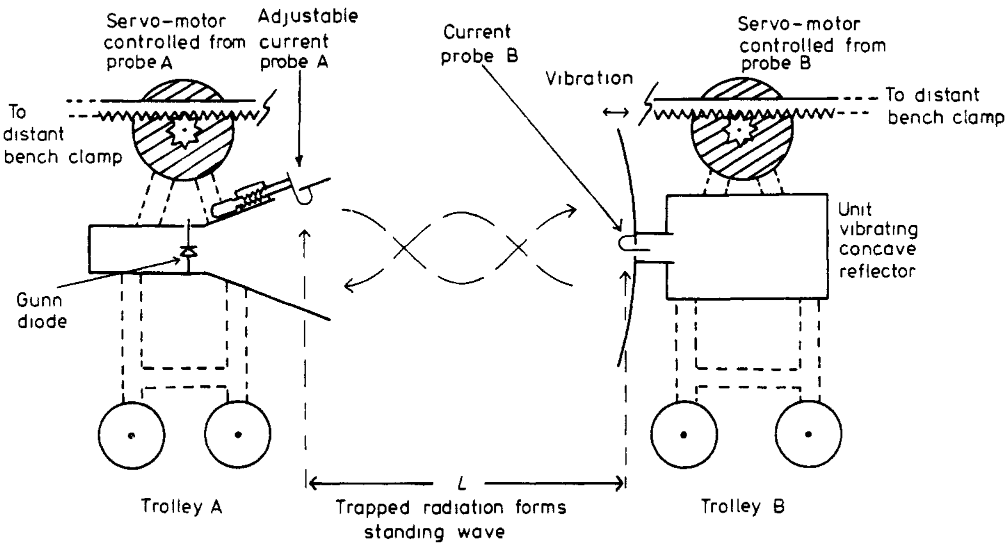

Figure 3. The freely floating phase-locked cavity. The distance L is maintained constant by independent sensing and control on each trolley. This effectively amplifies the very weak control exerted by the normal boundary conditions although the speed of response is degraded. The independent trolleys accelerate and move as though they were a single solid body upon the application of a horizontal force applied to one trolley only. Upon removal of the force the system coasts at the terminal velocity, still maintaining L constant.

'cavity' was located at a maximum of the transverse magnetic component of the standing-wave system formed between the horn and the concave mirror. Although both ends of the etalon were independent and freed from the frame of reference of the laboratory, both ends were locked onto the standing wave formed between them but had no other relevant physical connection.

It was found that this system formed a remarkably rigid rod with a breaking stress of about 2 kg. It responded immediately to very small changes in the refractive index of the intervening space clearly showing that it maintained the same electromagnetic length to a surprisingly high degree of accuracy, well within the excursion of the oscillating mirror. The application of a small force to either carriage caused the complete system to accelerate and no change in its length could be determined within this phase. Upon the removal of the motive force the system continued in its state of motion consistent with Newton's laws.

It was, of course, not possible to observe the macro-quantized nature of the acceleration as the internal delay time was less than a nanosecond and would also have been smoothed out by the response of the servo-systems. A variety of analogue delay systems may be used, however, to demonstrate the staircase effect.

The technique clearly demonstrated that a rigid rod and a proper unit of length could be identified with an ideal system of this kind and that the principle could be applied to any problem involving acceleration, whether kinematic or gravitational.

As a fall-out in applied physics the system showed that surfaces such as those in radio or even optical telescopes could be servoed with reasonable ease to accuracies at least of the order of one thousandth of the controlling wavelength.

11. Conclusions

We make the following conclusions:

(i) The origin of inertia is local and a direct result of the finite extension of all mass and the invariance of the local velocity of light.

(ii) Although no state of absolute translational velocity may be recognized, the state of acceleration may be clearly distinguished from the state of non-acceleration without reference to other bodies.

(iii) As rotation of a physical body renders it subject to acceleration, the inert state of non-rotation is unique in the spectrum of rotations.

(iv) The acquisition of a different inertial state is quantized.

(v) Electrons, and, we would hazard, all particles having an inertial rest mass, consist of trapped radiation. If this is so, it follows that intrinsically stable particles are only formed from a few precise frequencies of radiation.

(vi) The proper units of length and time in the physical world are bound up in the electron and are directly associated with the local wavelength and frequency corresponding to pair production. Thus proper clocks occur wherever and whenever electron pairs are formed at any epoch anywhere in the universe.

(vii) The concept of a phase-locked cavity may be used in all problems involving measurements under acceleration and rotation.

Unlike Mach's principle, the mechanism that we have discussed accounts for the quantized behaviour of interactions with matter. It permits, but does not necessarily require, the presence of static electric and magnetic fields associated with the particles. It predicts that the quantized response is essentially associated with the internal wave system and that the transfer function is quantized when the applied signal is classical continuous wave radiation. In the reciprocal process, however, short bursts of radiation may be transmitted back into space, but the cause of these short wave trains is the quantized transfer function of the *internal* system. Subsequent interactions of the wave trains in free and empty space are then a linear process consistent with Fourier theory and no other 'photon'–'photon' interaction is to be expected in free and empty space within the first-order predictions of the theory.

We note that our results are in no way at variance with either the special or general theories of relativity. Indeed they specify, for the first time, the proper local units on which both these theories are based.

Although this paper was intended only to be concerned with the origin of inertia, a referee has suggested that we might add a few words about the possible implications for the structure and other properties of the electron. This we now do on the understanding that the following discussion is, at this stage, entirely speculative. The analysis in this paper has been concerned with a one-dimensional system, for this is sufficient to demonstrate the inertial principle. In the case of the electron it becomes necessary to consider the remaining spatial dimensions and at the same time one must produce a model which is endowed with the principal properties of the natural particle. We would draw attention to the form of the constant in large parentheses in equation (5). For naturally trapped radiation m_0 is the mass of the electron and ν_0 is the pair production frequency. It appears therefore that only half of the energy associated with a photon for a free space wave of the frequency ν_0 is trapped in the particle and its electromagnetic wave properties may not be those of the familiar freely propagating wave of Maxwell's equations. The other half of the photon energy is carried by the anti-particle which must therefore be formed at the same time. One possible model of the electron was referred to briefly in an early popular account of this work (Jennison 1975). This tentative model included electron spin and suggested a method for obtaining the static electric and magnetic fields without a central infinity by the synchronous rotation of a wave field. It relies on a corollary of some recent work on rotation (Jennison 1963, 1964, Davies and Jennison 1975, Ashworth and Jennison 1976, Jennison and Ashworth 1976). It is interesting to note that in this and similar models based upon the concept of the phase-locked cavity, an indeterminacy arises from the fact that the phase of the trapped wave is completely inaccessible to prior observation. This indeterminacy will therefore be reflected in the mechanics of interactions or collisions with the particle such as those in the Compton effect (Ashworth and Jennison 1974, final paragraph).

Finally, it may be of interest that one of us has already drawn attention to the possibility that the principle of a phase-locked cavity may apply to ball lightning (Jennison 1973). If there is a specific metre wavelength at which phase-locking can take place, the field strength of the trapped wave may be sufficient to excite the ambient gas but the total inertial mass of the wave system will be trivial compared to the size of the ball. Ball lightning, on the other hand, is not usually observed in pairs, so that it may be necessary to consider two contra-rotating wave systems within a single ball.

Acknowledgments

We are grateful for the help of M A C Jennison in constructing the freely floating phase-locked cavity. One of us, A J D , is indebted to the Science Research Council for a studentship.

References

Ashworth D G and Jennison R C 1974 *J. Phys. A: Math., Nucl. Gen.* **7** 803–6
—— 1976 *J. Phys. A: Math. Gen.* **9** 35–43
Davidson W 1957 *Mon. Not. R. Astron. Soc.* **117** 212–4
Davies P A and Jennison R C 1975 *J. Phys. A: Math. Gen.* **8** 1390–7
Einstein A 1905 *Ann. Phys., Lpz.* **17**
Jennison R C 1963 *Nature* **199** 739–41
—— 1964 *Nature* **203** 395–6
—— 1973 *Nature* **245** 95
—— 1975 *Nucleus* (*University of Kent Science Students' Journal*)
Jennison R C and Ashworth D G 1976 *J. Phys. A: Math. Gen* **9** 1257–9
Mach E 1908 *The Science of Mechanics: A Critical and Historical Account of its Development* (1960 Transl. T J McCormack, 6th edn (La Salle, Ill.: Open Court) p 283)
McCrea W H 1971 *Nature* **230** 96
Sciama D W 1953 *Mon. Not. R. Astron. Soc.* **113** 32–42