Newton’s Laws of Motion in Form of Riccati Equation

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We discuss two applications of Riccati equation to Newton’s laws of motion. The first one is the motion of a particle under the influence of a power law central potential \( V(r) = kr^\epsilon \). For zero total energy we show that the equation of motion can be cast in the Riccati form. We briefly show here an analogy to barotropic Friedmann-Robertson-Lemaître cosmology where the expansion of the universe can be also shown to obey a Riccati equation. A second application in classical mechanics, where again the Riccati equation appears naturally, are problems involving quadratic friction. We use methods reminiscent to nonrelativistic supersymmetry to generalize and solve such problems.

PACS number(s): 45.20.-d, 11.30 Pb

I. INTRODUCTION

It is known that Riccati equations, in general of the type

\[
\frac{dy}{dx} = f(x) y^2 + g(x) y + h(x),
\]

find surprisingly many applications in physics and mathematics. For example, supersymmetric quantum mechanics [1], variational calculus [2], nonlinear physics [3], renormalization group equations for running coupling constants in quantum field theories [4] and thermodynamics [5] are just a few topics where Riccati equations play a key role. The main reason for their ubiquity is that the change of function

\[
y = -\frac{1}{f} \left( \frac{d}{dx} \log z - \frac{g}{2} \right),
\]

turns it into linear second-order differential equations of the form

\[
\frac{d^2 z}{dx^2} - \left( \frac{d}{dx} \log f \right) \frac{dz}{dx} - \left[ \frac{g^2}{4} - \frac{1}{2} \frac{dg}{dx} + h - \frac{d}{dx} \log f \right] z = 0,
\]

that stand as basic mathematical background for many areas of physics.

Since the Riccati equation is a widely studied nonlinear equation, knowing that the physical system under consideration can be brought into Riccati form has certainly many advantages.

It is therefore of interest to look for yet different physical problems which are governed by this first order nonlinear equation. This can be a starting point to new avenues in investigating analytical solutions of yet unsolved problems. In this paper we concentrate mainly on topics from classical mechanics and show that certain types of Newton’s laws of motion are equivalent to the Riccati equation.

II. THE POWER LAW CENTRAL POTENTIALS

After implementation of the angular momentum conservation law, the equation for the energy conservation in the case of a central potential \( V(r) \) is given by the standard expression

\[
E = \frac{1}{2} m \dot{r}^2 + \frac{l^2}{2mr^2} + V(r).
\]

Taking a derivative with respect to time of Eq. (4) results into a second fundamental equation of the form

\[
m \ddot{r} - \frac{l^2}{mr^3} + \frac{dV(r)}{dr} = 0.
\]

Specializing from now on to a power law potential

\[
V(r) = kr^\epsilon,
\]

where \( k \) is the coupling constant and the exponent \( \epsilon \) can be either positive or negative, we obtain from (5)

\[
V(r) = -\frac{m \ddot{r}r^\epsilon}{\epsilon} + \frac{l^2}{er^2}.
\]

Inserting the last equation in (4) gives

\[
\frac{1}{2} m \dot{r}^2 + \left( \frac{1}{2} + \frac{1}{\epsilon} \right) \frac{l^2}{mr^2} - \frac{m \ddot{r}}{\epsilon} - E = 0.
\]

Under the assumption of \( E = 0 \), this expression leads to a Riccati form. Obviously with \( E = 0 \), we restrict ourselves to the case \( k < 0 \). To explicitly derive from the Riccati equation we pass (as it is customary in central potential problems) to an angle \( \theta \) as a free variable (i.e., we consider \( r(\theta(t)) \)). With

\[
\dot{\theta} = \frac{l}{mr^2}, \quad r' = \frac{dr}{d\theta}
\]

and introducing

\[
\omega = \frac{r'}{r},
\]

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\[\text{arXiv:physics/0110066v2 [physics.class-ph] 18 Jan 2002} \]
it can be readily shown, after some algebraic manipulations, that (6) reduces to
\[ \omega' = \frac{\epsilon + 2}{2} \omega^2 + \frac{\epsilon + 2}{2}. \] (11)

This is the Riccati equation for the motion of a particle in a central power law potential assuming \( E = 0 \). It is worth noting that no information about the coupling constant \( k \) enters the Riccati equation (11). Essentially what we have shown is that any solution of (4) will also satisfy (11). The inverse is not necessarily true and should be examined in detail. Indeed, the coupling constant \( k \) should be explicitly contained in the solution for \( r(\theta) \) (see below).

A special case which deserves to be briefly mentioned is \( \epsilon = -2 \). With this exponent, the choice \( E = 0 \) is, in general, only possible if \( \frac{i^2}{2m} + k < 0 \). Then directly from (4) we conclude that \( \frac{i}{k} \) is a constant which, of course, is compatible with the Riccati equation (11). However, this constant cannot be determined by means of (11). This feature is also inherent in the general case.

To discuss the case \( \epsilon \neq 2 \), we first solve the Riccati equation (11). The solution can be easily found to be
\[ \omega(\theta) = \tan \left( \frac{\epsilon + 2}{2} \theta + \frac{\beta}{2} \right) = \frac{\sin((\epsilon + 2)\theta + \beta)}{\cos((\epsilon + 2)\theta + \beta) + 1}, \] (12)

where \( \beta \) plays a role of the integration constant. Going back to the definition of \( \omega \) in (10) we arrive at a solution for \( r(\theta) \)
\[ r(\theta) = \frac{R}{[1 + \cos((\epsilon + 2)\theta + \beta)]^{1/(\epsilon + 2)}}, \] (13)

where \( R \) is a constant. As in the case \( \epsilon = -2 \) this constant can only be determined by inserting (11) into (4). The result is
\[ R = \left( \frac{i^2}{m|k|} \right)^{1/2}. \] (14)

The last two equations represent then the analytical solution of the posed problem. We obtained this solution by transforming the original problem into a Riccati equation. It might be that the laws of motion in Riccati form are only a curiosity. Given, however, the fact that only a few analytical solutions of the central potential problem are known, it is certainly a useful curiosity. Furthermore, it is not excluded that this novel way opens new more general methods to solve problems in mechanics. In this context, we would like to mention here a yet different connection of the central potential problem with the Ermakov nonlinear differential equation (4). We refer to the following form of the latter equation (4)
\[ q(x) \frac{d^2 y}{dx^2} + y(x) \frac{d^2 q(x)}{dx^2} = \frac{1}{q^2(x)} f \left( \frac{y}{q} \right), \] (15)

which can be solved by the integrals
\[ \int \frac{dx}{q^2(x)} + a = \int \frac{d \left( \frac{x}{q} \right)}{\sqrt{\phi \left( \frac{x}{q} \right) + b}}, \] (16)

where \( a \) and \( b \) are integration constants and
\[ \phi(z) \equiv 2 \int f(z)dz. \] (17)

Taking \( p = \text{const} = m \) and suitably rescaling the distance \( r \) with the mass \( m \), equation (15) is essentially identical to (3). Indeed, in this case the integrals in (17) give
\[ t - t_0 = \frac{1}{m} \int_{r_0}^{r} \frac{dr_1}{\sqrt{2mV(r_1) - \frac{i^2}{r_1} + b}}, \] (18)

which, with a proper identification of \( b \), is the same as directly integrating (3). The interplay between the Ermakov equation and the central potential problems could be a useful tool of studying both problems. We conjecture that certain invariants of the Ermakov equation could be also applied to the central potential problems.

### III. COSMOLOGICAL ANALOGY

We want to point out here a beautiful but formal cosmological analogy to the results of the previous section. We recall that in deriving the Riccati equation (9) we relied on a power law potential (4), a new parameter \( \theta \) (the angle given in (9)), and the assumption \( E = 0 \). The analogy to cosmology is based on these observations. In Friedmann-Robertson-Walker spacetime the set of Einstein’s equations with the cosmological constant \( \Lambda \) set to zero reduce to differential equations for the scale factor \( a(t) \), which is a function of the comoving time \( t \). Together with the conservation of energy-momentum tensor they are given by
\[ 3\ddot{a}(t) = -4\pi G (\rho + 3p(\rho))a(t) \] (19)
\[ a(t)\ddot{a}(t) + 2\dot{a}^2(t) + 2\kappa = 4\pi G (\rho - p(\rho))a^2(t) \] (20)
\[ \dot{p}a^3(t) = \frac{d}{dt} \left( a^2(\rho + p(\rho)) \right). \] (21)

In the above \( G \) is the Newtonian coupling constant, \( p \) is the pressure, \( \rho \) is the density and \( \kappa \) can take the values 0, \( \pm 1 \). Choosing the equation of state to be barotropic
\[ p(\rho) = (\gamma - 1)\rho, \] (22)

fixes essentially \( \rho \) to obey a power law behaviour of the form
\[ \rho = \rho_0 \left( \frac{a}{a_0} \right)^{-3\gamma}, \]  

(23)

and the remaining equation for \( a(t) \) reduce to a single equation, viz

\[ \frac{\dot{a}(t)}{a(t)} + c \left( \frac{\dot{a}(t)}{a(t)} \right)^2 + c \frac{\kappa}{a^2(t)} = 0, \quad c \equiv \frac{3}{2}c - 1. \]  

(24)

Introducing the conformal time \( \eta \) by

\[ \frac{d\eta}{dt} = \frac{1}{a(\eta)}, \]  

(25)

it can be seen that (24) is equivalent to a Riccati equation in the function \( u = \frac{a}{\dot{a}} \), where the dot means derivation with respect to \( \eta \)

\[ u' + cu^2 + \kappa c = 0. \]  

(26)

This cosmological Riccati equation has been previously obtained by Faraoni [4] and also discussed by Rosu [10] in the context of late cosmological acceleration. The formal analogy to the mechanical case is obvious: the condition \( E = 0 \) corresponds to \( \Lambda = 0 \), the angle \( \theta \) is replaced by the conformal time \( \eta \), and whereas in the mechanical example we had a power law behaviour of the potential, the barotropic equation of state forces upon \( \rho \) to satisfy \( \rho \propto a^{-3\gamma} \). As (24) does not contain the coupling constant \( k \), the cosmological Riccati equation (26) loses the information about \( G \).

\section*{IV. QUADRATIC FRICTION}

Starting with a constant force \( g \) (free fall, constant electric field, etc) and adding a quadratic friction with a positive friction coefficient \( \nu > 0 \), we have, per excellence, a Riccati equation for the Newton’s law of motion

\[ \dot{v} = g' - \alpha v^2, \]  

(27)

with \( g' \equiv g/m \) and \( \alpha \equiv \nu/m \). The general solution (which for reasons to be seen later in the text we denote by \( v_p \)) involves a free parameter \( \lambda \) and reads [12]

\[ v_p(t; g', \alpha, \lambda) = \frac{r}{\alpha} \left( e^{rt} - \lambda e^{-rt} \right), \quad r = \alpha g'. \]  

(28)

In the following we borrow some techniques from supersymmetric quantum mechanics. However, we do not follow strictly the supersymmetric scheme as the purposes in the quantum case and the mechanical case are quite different. We define a new time-dependent force by

\[ \gamma(t; g', \alpha, \lambda_1) \equiv \dot{v}_p(t; g', \alpha, \lambda) + \lambda_1 v_p^2(t; g', \alpha, \lambda). \]  

(29)

with a new parameter \( \lambda_1 > 0 \). We emphasize that (29) is a definition given through the solution (28). From (27) it can be then deduced that the following equivalent form of \( \gamma \) can be obtained

\[ \gamma = g' - (\alpha - \lambda_1) v_p^2. \]  

(30)

This resembles supersymmetric quantum mechanics and we might be tempted to compare \( v_p \) to Witten’s superpotential.

To the new force we again add a quadratic friction with a friction coefficient \( \lambda_1 \) such that the new equation of motion becomes

\[ \dot{v} = \gamma - \lambda_1 v^2. \]  

(31)

This has the advantage that per construction \( v_p \) is a particular solution of (31). Equipped with this fact, one can proceed to construct the general solution which is a standard procedure in the general theory of the Riccati equation. Before doing so, it is instructive to dwell upon the physical meaning of the new force \( \gamma \). Imposing \( g' - (\alpha - \lambda_1) v_p^2 > 0 \), it can be seen that \( \gamma > 0 \). Moreover, as obvious from (28) and (31), \( \gamma \) goes to a constant for large \( t \) and has a kink-like behaviour. We can then envisage a situation where \( \gamma \) is a ‘switch-on’ function for a force becoming constant at some time. As mentioned above, by construction the problem (24) is solvable because \( v_p \) is a particular solution of (31). By invoking the standard Bernoulli ansatz for the general solution \( v_g \), namely

\[ v_g = v_p + \frac{1}{\sqrt{V}}, \]  

we arrive at the differential equation (special case of the Bernoulli equation) for \( V \)

\[ \dot{V} = 2\lambda_1 v_p V + \lambda_1. \]  

(33)

Writing \( v_p \) as

\[ v_p = -\frac{1}{\lambda_1} \frac{\dot{W}_p}{W_p}, \]  

(34)

where

\[ W_p = e^{-\lambda_1 t} \int v_p dt, \]  

(35)

one is led to the solution for \( V \)

\[ V = \frac{\lambda_1}{W_p} \int W_p^2 dt + C, \]  

(36)

The general solution is then given by

\[ v_g = v_p + \frac{W_p^2}{\lambda_1 \int W_p^2 dt + C}. \]  

(37)

The initial value problem, \( v(0) = v_0 \), is solved by fixing \( C \) through
\[ v_0 = \frac{r}{\alpha} \left( \frac{1 - \lambda}{1 + \lambda} \right) = \frac{1}{C}. \]  

(38)

Up to integrals, the equation of motion (31) is solved. Setting \( \lambda = e^{-2\delta} \), we can rewrite (28) in the more convenient form

\[ v_p = \frac{r}{\alpha} \tanh(rt + \delta). \]  

(39)

Then \( W_p \) can be computed explicitly

\[ W_p = \frac{1}{[\cosh(rt + \delta)]^{\lambda_1/\alpha}}. \]  

(40)

It suffices to assume \( \lambda_1 = n\alpha, n \in \mathbb{N} \) leading to integrals of the type \( \int \cosh^{-n}(x)dx \), which can be solved in a closed analytical form by recursion formulae. Of course, the procedure outlined here can be generalized by starting with more complicated forces instead of the constant one.

IV. CONCLUSION

In this paper we have pointed out the usefulness of the Riccati equation in studying certain mechanical problems. We derived a Riccati equation for a central potential problem of the power law type assuming \( E = 0 \). This led us to an analytical solution of the problem. In a second step, we generalized the system of a constant force plus a quadratic friction to a time-dependent force and friction. We argued that this time-dependent force serves as a ‘switch-on’ function. The problem turned out to be solvable by means of a construction similar to supersymmetric quantum mechanics. As indicated in the text, both applications can be generalized.

ACKNOWLEDGMENT

The first author thanks CONACyT for financial support through a Catedra Patrimonial fellowship.

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