Families of Periodic Solutions of Systems
Having Relatively Invariant Line Integrals*

by

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12. **Abstract:** This report generalizes to all systems having relatively invariant line integrals a known theorem about conservative Lagrangian systems, which is roughly to the effect that in any given family of periodic solutions the period is at most a function of the energy alone.
    The energy function is hereby replaced by a certain function, $H(x_1, \ldots, x_n)$ which is known to be a first integral of the given system, $\frac{dx_i}{dt} = X_i(x_1, \ldots, x_n)$, $i = 1, \ldots, n$, and which furthermore satisfies relations of the form,
    \[ \sum (\frac{\partial A_i}{\partial x_j} - \frac{\partial A_j}{\partial x_i}) x_j = \frac{\partial H}{\partial x_i}, \quad i = 1, \ldots, n, \]
    where the A's are known because of the known relatively invariant line integral.

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The purpose of this paper is to generalize to all systems having relatively invariant line integrals a known theorem about Lagrangian (or Hamiltonian) systems of differential equations. This known theorem is roughly to the effect that in any given family of periodic solutions the period is at most a function of the energy constant alone; that is, it does not depend upon the parameters of the family except in so far as the energy is a function of these parameters. An exception may occur, however, if the energy itself is independent of the parameters.

The history of this particularly elegant theorem began over eighty years ago, but the only presentation in a standard treatise known to me is in the book of A. Wintner, "Analytical Foundations of Celestial Mechanics," Princeton University Press, 1941, pp. 75, 74, and p. 414, where reference to the older literature is to be found. The only flaw in this treatment is the omission of mention of the exception noted above in case the energy constant is independent of the parameters. A satisfactory treatment in this respect is given by G. Herglotz, among the collection of papers by various authors published in book form: "Probleme der Astronomie; Festschrift für Hugo v. Seeliger," Berlin 1924, pp. 197-199.

The generalization given in this paper (cf. below the statement of the main theorem) is a bit more than a mere extension of the classical theorem to the Pfaffian equations of Birkhoff (which, by a suitable transformation on the dependent variables, can be written in Hamiltonian form, at least in the neighborhood of a given periodic solution); for we make no assumption

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about the rank of the skew-symmetric matrix \( \partial A_j / \partial x_j - \partial A_j / \partial x_i \). The order of the system is not even assumed to be even.

In order to summarize certain preliminary facts, we begin with a statement of the following known lemmas:

**Lemma 1.** Consider the system

\[
(1) \quad \frac{dx_i}{dt} = X_i(x_1, \ldots, x_n), \quad i = 1, \ldots, n,
\]

and the line integral

\[
(2) \quad \int_C \sum_{i=1}^{n} A_i(x_1, \ldots, x_n) dx_i
\]

in which the X's are of class C' and the A's of class C'' in a domain R of n-space. A necessary and sufficient condition that (1) admit (2) as a relatively invariant line integral (in the sense of Poincaré) is that there should exist a function H of class C'' in this domain such that

\[
(3) \quad \sum_{j=1}^{n} \left( \frac{\partial A_i}{\partial x_j} - \frac{\partial A_j}{\partial x_i} \right) X_j = \frac{\partial H}{\partial x_i},
\]

identically in R. (Cf. E. Goursat, Leçons sur le problème de Pfaff, Paris, 1922, p. 219; but the understanding reader can probably construct his own proof far more easily than by deriving the lemma as a special case of various general results in the literature. Actually the lemma is not essential for the rest of the paper except to show the significance of (3), which is henceforth assumed.)

**Lemma 2.** If H is any function satisfying (3), then \( H(x_1, \ldots, x_n) \) is a first integral of (1). For \( \sum_i (\partial H / \partial x_i) X_i = \sum_{i,j} (\partial A_i / \partial x_j - \partial A_j / \partial x_i) X_i X_j \equiv 0 \) because of the skew-symmetry of \( \partial A_j / \partial x_i - \partial A_i / \partial x_j \).
We now state our main result:

**THEOREM.** We assume again that the $X$'s are of class $C'$, that the $A$'s and $H$ are of class $C''$ and that (3) holds. We also assume that we have a family of solutions of (1) of class $C''$ depending on $m$ parameters $c_1, \ldots, c_m$, and that these solutions are periodic with a period $T = T(c_1, \ldots, c_m) = T(c)$ which, considered as a function of the parameters, is of class $C'$. We also denote by $h(c_1, \ldots, c_m) = h(c)$ the value of the first integral $H$ for the solution with parameter values $(c)$. Then all the Jacobians,

$$\frac{\partial (h, T)}{\partial (c_k, c_h)} = 0, \quad h, k = 1, 2, \ldots, m,$$

identically.

To prove this, the family of solutions is represented in the form

$$x_i = x_i(t, c_1, \ldots, c_m) = x_i(t, c) = x_i(t + T(c), c), \quad i = 1, \ldots, n.$$  

Setting $t = 0$ and differentiating both sides of the last equality with respect to $c_k$, we find that

$$\frac{\partial x_i}{\partial c_k}{\bigg|}_{t=0} = \dot{x}_i \frac{\partial T}{\partial c_k}{\bigg|}_{t=T(c)} + \frac{\partial x_i}{\partial c_k}{\bigg|}_{t=T(c)}.$$

Here, of course, $\dot{x}_i$ refers to the derivative of $x_i(t, c)$ with respect to $t$. Let $S = S(c) = \int_0^T (\sum_{i=1}^n A_i \dot{x}_i + H) dt$, in which the arguments of the $A$'s and $H$ are understood to be given by (5). Differentiating this last we find that

$$\frac{\partial S}{\partial c_k} = \left( \sum_{i=1}^n A_i \dot{x}_i + H \right) \frac{\partial T}{\partial c_k}{\bigg|}_{t=T(c)}$$

$$+ \int_0^T \left( \sum_{i=1}^n \frac{\partial x_i}{\partial c_k} + \sum_{i,j} \frac{\partial A_i}{\partial x_j} \frac{\partial x_i}{\partial c_k} \dot{x}_j + \sum_{j} \frac{\partial H}{\partial x_j} \frac{\partial x_i}{\partial c_k} \right) dt.$$
The first terms in the integrand may be integrated by parts:

\[
\int_0^{T(c)} \left( \sum_i A_i \frac{\partial x_i}{\partial c_k} \right) dt = \sum_i A_i \frac{\partial x_i}{\partial c_k} \bigg|_{t=T(c)} - \sum_i A_i \frac{\partial x_i}{\partial c_k} \bigg|_{t=0}
\]

\[- \int_0^{T(c)} \left( \sum_{i,j} \frac{\partial A_i}{\partial x_j} \frac{\partial x_i}{\partial c_k} \right) dt.
\]

We now interchange the indices \(i\) and \(j\) in the double summation in the last term, and we also reduce the first two terms with the help of (6) and the fact that \(A_i \bigg|_{t=T(c)} = A_i \bigg|_{t=0}\) from the given periodicity of the family. We thus obtain

\[
\int_0^{T(c)} \left( \sum_i A_i \frac{\partial x_i}{\partial c_k} \right) dt = - \sum_i A_i \frac{\partial x_i}{\partial c_k} \bigg|_{t=T(c)} - \int_0^{T(c)} \left( \sum_{i,j} \frac{\partial A_i}{\partial x_j} \frac{\partial x_i}{\partial c_k} \right) dt.
\]

Using this result in (7) and also setting \(\dot{x}_i = x_i\), since (1) is satisfied, we find that

\[
\frac{\partial S}{\partial c_k} = H \frac{\partial T}{\partial c_k} \bigg|_{t=T(c)} + \int_0^{T(c)} \left( \sum_j \left( \sum_i \frac{\partial A_i}{\partial x_j} - \frac{\partial A_i}{\partial x_i} \right) x_i + \frac{\partial H}{\partial x_j} \frac{\partial x_i}{\partial c_k} \right) dt.
\]

Hence, finally from (3), lemma 2, and the definition of \(h\), we have the very simple formula,

\[
\frac{\partial S}{\partial c_k} = h(c) \frac{\partial T}{\partial c_k}, \quad k = 1, 2, \ldots, m.
\]
If \( T \) were known to be of class \( C'' \) the same would be true of \( S \) and the fact that \( \frac{\partial^2 S}{\partial c_k \partial c'_l} = \frac{\partial^2 S}{\partial c'_l \partial c_k} \) would lead at once to (4).

Since, however, we assume only that \( T \) is of class \( C' \), we arrive at the same result by the device of letting \( W = hT - S \), so that \( \frac{\partial W}{\partial c_k} = \frac{\partial h}{\partial c_k} T + h \frac{\partial T}{\partial c_k} \) and the same is true of \( W \), and we arrive at (4) from the fact that \( \frac{\partial^2 W}{\partial c_k \partial c'_l} = \frac{\partial^2 W}{\partial c'_l \partial c_k} \).

In the theorem just proved we have deliberately left our conclusion in the form (4), because of the difficulty of drawing any completely general conclusions on functional dependence from it. Several not mutually exclusive cases may be considered.

**Case 1.** If not all of the derivatives of \( h \) vanish at a point \((c^0)\), then there is a function \( \varphi \) of one variable of class \( C' \) such that, \( T(c) = \varphi(h(c)) \) in the neighborhood of \((c^0)\). This may be regarded as the general case and, for Hamiltonian systems, it is the basis of the rough statement in our first paragraph.

**Case 2.** If not all of the derivatives of \( T \) vanish at a point \((c^0)\), then there is a function \( \psi \) of one variable of class \( C' \) such that, \( h(c) = \psi(T(c)) \) in the neighborhood of \((c^0)\). This may also be regarded as the general case; but, that it is not coextensive with Case 1, even for Hamiltonian systems, will be shown below by means of examples.

**Case 3.** If all the derivatives of both \( T \) and \( h \) vanish near \((c^0)\) identically, then, of course, both \( T \) and \( h \) are constants, and we have no difficulty in writing either \( T = \varphi(h) \) or \( h = \psi(T) \), or more inclusively

\[
(9) \quad G(T, h) = 0, \quad |G_T| + |G_h| \neq 0.
\]

**Case 4.** If all the derivatives of both \( T \) and \( h \) vanish at \((c^0)\) but not identi-
ally in the neighborhood of \((c^0)\), we have a situation shunned by most elementary writers on functional dependence. If we assume that \(T\) and \(h\) are analytic, we can still assert the validity of (9) for a suitably chosen \(G\) (cf. G. A. Bliss, Am. Math. Soc. Colloquium Publications, 1913, pp. 67-70). Otherwise the situation is obscure.

We close with mention of a few examples of systems in which \(T\) varies while \(h\) remains fixed, thus showing that Case 2 can occur without Case 1.

Any equilibrium point of any Hamiltonian system may be regarded as a family of periodic solutions having an arbitrary varying period, all with the same energy. But this example is so highly degenerate as to suggest the possibility of ruling out the exhibited phenomenon by some such requirement as that the functions \(x_i(t, c)\) of (5) should not reduce to mere constants.

Herglotz (loc. cit.) gives the example afforded by the motion of a particle attracted toward a fixed center by a force inversely proportional to the cube of its distance from the center. In this system the circular solutions form an isoenergetic family with varying period. He shows that this is the only possibility of this phenomenon in central force problems.

Other non-trivial examples, having nothing to do with the central force problem, have been devised but, for brevity, are here omitted.