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On sets filled by asymptotic solutions of differential equations


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ON SETS FILLED BY ASYMPTOTIC SOLUTIONS OF DIFFERENTIAL EQUATIONS

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Consider an ordinary differential equation

(1) \[ x' = f(t, x) \]

\[ x = (x_1, \ldots, x_n), \quad f = (f_1, \ldots, f_n). \]

Assumption I. Suppose that the domain \( D \) of \( f(t, x) \) is open, \( f(t, x) \) is continuous on \( D \) and through each point \( A : t = a_0, \quad x = a = (a_1, a_2, \ldots, a_n) \) of \( D \) passes only one integral \( x = x(t, A) \) of (1).

Denote by \((\alpha(A), \beta(A))\) the maximal interval on which there exists the integral passing through \( A \). We shall denote

\[ X(t, A) = (t, x(t, A)) \quad \text{for} \quad t \in (\alpha(A), \beta(A)). \]

Let \( E \) be an open subset of \( D \). In the following we shall deal with the set \( Z(E) \) of such points \( A \), that \( X(t, A) \in E \) for

\[ a_0 \leq t < \infty. \]

Obviously set \( Z(E) \) depends on both set \( E \) and system (1). It is evident that \( E \subset F \) implies \( Z(E) \subset Z(F) \). Let \( \varphi \) be a family of subsets \( F \) of \( D \). We shall consider the following properties of equation (1).

Property I (of equation (1) in respect to \( E \) and \( \varphi \)). — For every \( F \in \varphi, Z(E) \cap F \) is empty or consists of one point.

Property II. — For every \( F \in \varphi \), \( Z(E) \cap F \) is not empty.

Let \( I^+(A) \) denote the set of all points \( B = X(t, A) \) for \( t \geq a_0 \).
We say that the point \( A \in P(G) \cap D \), where \( P(G) \) denotes the boundary of an open set \( G \), is the point of egress from \( G \) (with respect to equation (1) and set \( D \)) if there exists such an integral \( x(t) \) of (1) and a positive number \( \varepsilon > 0 \) that
\[
x(a_0) = a \quad \text{and} \quad (t, x(t)) \in G
\]
for \( a_0 - \varepsilon < t < a_0 \) (under Assumption I, \( X(t, A) \in G \) for \( a_0 - \varepsilon < t < a_0 \)). If no point of \( P(G) \) is a point of egress from \( G \) then \( A \in G \) implies \( I^+(A) \subset G \). If Property I is satisfied and \( B \in Z(E) \cap F \) then \( (F - B) \cap Z(E) = \emptyset \), where \( F - B \) denotes the set of all points of the set \( F \) except the point \( B \). It follows that for every \( A \in F \), \( A \neq B \) either \( I^+(A) \sim e \in E \) or \( \beta(A) < \infty \). Let \( G \) be such a set that \( G \cap E \) has no common point with a plane \( t = c > a_0 \) where \( G \) denotes the closure of \( G \), then \( I^+(A) \subset G \) implies \( A \sim e \in Z(E) \).

**Lemma.** Suppose Assumption I and the following conditions. For each set \( G_i \) (i = 1, \ldots) \( G_i \cap E \) is contained in a halfspace \( t < c_i \). No point of \( P(G_i) \) is a point of egress. Set \( F \) satisfies inclusion \( F - 0 \subset \bigcup G_i \).

Then \( (F - 0) \cap Z(E) = \emptyset \).

**Theorem 1.** Suppose Assumption I and the following conditions. The intersection \( E(s) \) of a given set \( E \) and the plane \( t = s \) satisfies the inequality \( \text{diam}(E(t)) < p(t) \), \( \text{where p(t) is a positive function continuous on } (-\infty, \infty) \). No point of \( P(G_i) \) is a point of egress in respect to the equation
\[
x' = f(t + a_0, x + a(t)) - f(t + a_0, a(t)),
\]
where \( a_0 \) is a real number and \( x = a(t) \) is such a Lipchitzian function that the right side of the equation is defined. Set \( F \) satisfies inclusion \( F - 0 \subset \bigcup G_i \). For any \( i \) and \( s \) there exists a constant \( c(i, s) \) that \( \text{dist} (G_i(t), 0) \geq p(t + s) \) for \( t \geq c(i, s) \), where \( G_i(s) \) is the intersection of \( G_i \) and the plane \( t = s \).

Under these assumptions if \( A \in Z(E) \), then
\[
(F(A) - A) \cap Z(E) = \emptyset,
\]
where \( F(A) \) denotes set obtained from \( A \) by translation of \( \mathbb{R}^{n+1} \) transforming \( 0 \) on \( A \).
Theorem 2. — If assumptions of Theorem 1 are satisfied and F is a plane then equation (1) possesses property I in respect to E and the family of planes parallel to F (and of the same dimension).

Suppose now that set F is a plane and in the coordinate system \( t, x = (u, \nu), u = (u_1, \ldots, u_k), \nu = (\nu_1, \ldots, \nu_{n-k}) \) it has the equation \( t = 0, u = 0 \). Now Property I (for the family of planes \( t = c_0, u = (c_1, \ldots, c_k), c_i \) arbitrary) is necessary and sufficient for set \( Z(E) \) to be the graph of a single-valued function \( \nu = q(t, u) \). Putting \( g = (f_1, \ldots, f_k), h = (f_{k+1}, \ldots, f_n) \) system (1) takes the form

\[
(2) \quad u' = g(t, u, \nu), \quad \nu' = h(t, u, \nu).
\]

The following result formulated in terms of inequalities can be obtain from Theorem 1 formulated in terms of sets (1)

Theorem 3. — Suppose that system (2) satisfies Assumption I and that the functions \( g(t, u, \nu), h(t, u, \nu) \) for \( (t, u, \nu) \in D \), \( (t, \bar{u}, \bar{\nu}) \in D \) satisfy inequalities

\[
(3) \quad (g(t, u, \nu) - g(t, \bar{u}, \bar{\nu})) (u - \bar{u}) \leq \gamma(t) (u - \bar{u})^2
\]

for \( |\nu - \bar{\nu}| = |u - \bar{u}| \), where \( |z| \) denotes Euclidean distance of point \( z \) from 0,

\[
(4) \quad (h(t, u, \nu) - h(t, \bar{u}, \bar{\nu})) (\nu - \bar{\nu}) \geq \gamma(t) (\nu - \bar{\nu})^2,
\]

for

\[
|u - \bar{u}| \leq |\nu - \bar{\nu}|
\]

where \( \gamma(t) \) is a function summable in every finite interval, and such that

\[
\int_0^\infty \gamma(s) \, ds = \infty,
\]

then set \( Z \) of points \( A \) lying on the integrals of (2) (remaining in \( D \)) bounded for \( a_0 \leq t < \infty \) is a graph of a single-valued function \( \nu = q(t, u) \) defined in a certain set \( S(S \subset \mathbb{R}^{k+1}) \) satisfying the Lipschitz condition with respect to all the variables.

(1) Such kind of formulation was suggested by T. Wazewski.
and in particular the condition

\[ |q(t, u) - q(t, \bar{u})| \leq |u - \bar{u}| \]

in the set \( S \) or the set \( Z \) is an empty set.

Theorem 3 is a particular case of theorem 2 in [1].

Now for illustration of Property II we present a variant of an example from [2].

Let system (2) satisfy Assumption I on a neighbourhood \( D \) of the set \( H : |u| \leq 1, |\nu| \leq 1, -\infty < t < \infty \). Moreover suppose that \( g(t, u, \nu)u < 0 \) for \( |u| = 1, |\nu| \leq 1 \) and arbitrary \( t, h(t, u, \nu) > 0 \) for \( |\nu| = 1, |u| \leq 1 \) and arbitrary \( t \).

Under these assumptions for every \( \bar{u}, |\bar{u}| < 1 \) and arbitrary \( \bar{t} \), there exists \( \bar{\nu} \), that \( I^+ (\bar{t}, \bar{u}, \bar{\nu}) \in H \).

BIBLIOGRAPHY
