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On the existence of homoclinic type solutions of a class of inhomogeneous second order Hamiltonian systems

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Abstract
We show the existence of homoclinic type solutions of second order Hamiltonian systems of the type
\[ \ddot{q}(t) + \nabla_q V(t, q(t)) = f(t), \]
where \( t \in \mathbb{R} \), the \( C^1 \)-smooth potential \( V: \mathbb{R} \times \mathbb{R}^n \rightarrow \mathbb{R} \) satisfies a relaxed superquadratic growth condition, its gradient is bounded in the time variable, and the forcing term \( f: \mathbb{R} \rightarrow \mathbb{R}^n \) is sufficiently small in the space of square integrable functions. The idea of our proof is to approximate the original system by time-periodic ones, with larger and larger time-periods. We prove that the latter systems admit periodic solutions of mountain-pass type, and obtain homoclinic type solutions of the original system from them by passing to the limit (in the topology of almost uniform convergence) when the periods go to infinity.

1 Introduction
During the past two decades there have been numerous applications of methods from the calculus of variations to find periodic, homoclinic and heteroclinic solutions for Hamiltonian systems. Many of the striking results that have been obtained by variational methods can be found in the well-known monographs of Ambrosetti and Coti Zelati [3], Ekeland [8], Hofer and Zehnder [9], Mawhin and Willem [16], as well as in the review articles of Rabinowitz [19, 20].

The aim of this paper is to prove the existence of solutions of the second order Hamiltonian system
\[ \begin{align*}
\ddot{q}(t) + \nabla_q V(t, q(t)) &= f(t), \quad t \in \mathbb{R}, \\
\lim_{t \to \pm \infty} q(t) &= \lim_{t \to \pm \infty} \dot{q}(t) = 0,
\end{align*} \tag{1} \]
where the \( C^1 \)-smooth potential \( V: \mathbb{R} \times \mathbb{R}^n \rightarrow \mathbb{R} \) satisfies a relaxed superquadratic growth condition, its gradient \( V_q: \mathbb{R} \times \mathbb{R}^n \rightarrow \mathbb{R}^n \) is uniformly bounded in the time variable on every compact subset of \( \mathbb{R}^n \), and the norm of the forcing term \( f: \mathbb{R} \rightarrow \mathbb{R}^n \) in the space of square integrable functions is smaller than a bound that we state below in our main theorem.

As homoclinic type solutions are global in time, it is reasonable to use global methods to find them rather than approaches based on their initial value problems. The homogenous systems of (1), i.e. when \( f \equiv 0 \), have been studied extensively under the assumption of superquadratic or subquadratic growth of the potential \( V(t, q) \) as \( |q| \to \infty \). Indeed, there are many results on homoclinic solutions for subquadratic Hamiltonian systems (cf. e.g. [20]). The first variational results for homoclinic solutions of first order Hamiltonian systems with superquadratic growth were found by V. Coti Zelati, I. Ekeland and E. Séré in [6] for time-periodic Hamiltonians. Corresponding results for second order Hamiltonian systems were obtained in [18] and [7]. S. Alama and Y.Y. Li [1] showed that asymptotic periodicity in time actually suffices to get a homoclinic solution, and E. Serra, M. Tarallo and S. Terracini [21] weakened their periodicity condition to almost periodicity in...
Theorem 1.1. also gives an answer to the question how large the forcing term can be.

Let us point out that under the above assumptions the Hamiltonian system (1) has the trivial type solutions exist when \( f \) is sufficiently small. Our purpose is to generalize Theorem 1.1 of [5], which deals with the existence of solutions of the inhomogeneous systems (1) under the rather restrictive assumption that the potential \( V \) is of the special form

\[
V(t, q) = -\frac{1}{2}|q|^2 + a(t)G(q),
\]

where \( a: \mathbb{R} \to \mathbb{R} \) is a continuous positive bounded function and \( G: \mathbb{R}^n \to \mathbb{R} \) is of class \( C^1 \) and satisfies the Ambrosetti-Rabinowitz superquadratic growth condition. Here, instead, the potential is of the more general form

\[
V(t, q) = -K(t, q) + W(t, q)
\]

with \( C^1 \)-smooth potentials \( K \) and \( W \) such that

\[ K(t, q) \leq (q, \nabla_q K(t, q)) \leq 2K(t, q) \]

\[ \nabla_q W(t, q) = o(|q|) \text{ as } |q| \to 0 \text{ uniformly in } t \in \mathbb{R}, \]

\[ 0 < m := \inf \{W(t, q) : t \in \mathbb{R} \wedge |q| = 1\} > 0. \]

Our purpose is to generalize Theorem 1.1 of [5], which deals with the existence of solutions of the inhomogeneous systems (1) under the rather restrictive assumption that the potential \( V \) is of the form.

The idea of our proof, which we give in the following second section, is to approximate the original system (1) by time-periodic ones, with larger and larger time-periods. We show that the approximating systems admit periodic solutions of mountain-pass type, and obtain a homoclinic type solution of the original system from them by passing to the limit (in the topology of almost uniform convergence) when the periods go to infinity. Finally, we discuss some examples of Theorem 1.1 in Section 3.
We now fix $V$ and square integrable map. Assume that

\[ \nabla \]

Theorem 2.2 (Approximative Method, [15])

For each $t$ is non-increasing. Hence, for every $\zeta$ in the rest of the proof that $\zeta \neq 0$ and $q \neq 0$. Then it follows from \((C_b)\) that, for every $q \neq 0$ and $t \in \mathbb{R}$, the function $z: (0, +\infty) \to \mathbb{R}$ defined by

\[ z(\zeta) = W \left( t, \frac{q}{|q|} \right) \zeta^\mu \]

is non-increasing. Hence, for every $t \in \mathbb{R}$,

\[ W(t, q) \leq W \left( t, \frac{q}{|q|} \right) |q|^{\mu}, \text{ if } 0 < |q| \leq 1 \]  \hspace{1cm} (3)

and

\[ W(t, q) \geq W \left( t, \frac{q}{|q|} \right) |q|^{\mu}, \text{ if } |q| \geq 1. \]  \hspace{1cm} (4)

We now fix $\zeta \in \mathbb{R} \setminus \{0\}$, $q \in E_k \setminus \{0\}$ and set

\[ A_k = \{ t \in [-k, k]: |\zeta(q(t))| \leq 1 \}, \]
\[ B_k = \{ t \in [-k, k]: |\zeta(q(t))| \geq 1 \}. \]

By (4), we get

\[ \int_{-k}^{k} W(t, \zeta(q(t))) dt \geq \int_{B_k} W(t, \zeta(q(t))) dt \geq \int_{B_k} W \left( t, \frac{\zeta(q(t))}{|\zeta(q)|} \right) |\zeta(q(t))|^{\mu} dt \]
\[ \geq m \int_{B_k} |\zeta(q)|^{\mu} dt \geq m \int_{-k}^{k} |\zeta(q)|^{\mu} dt - m \int_{A_k} |\zeta(q)|^{\mu} dt \]
\[ \geq m|\zeta|^{\mu} \int_{-k}^{k} |q(t)|^{\mu} dt - 2km, \]

which completes the proof.

Further, to prove Theorem 1.1, we need the following approximative method.

**Theorem 2.2** (Approximative Method, [15]). Let $f: \mathbb{R} \to \mathbb{R}^n$ be a non-trivial, bounded, continuous and square integrable map. Assume that $V: \mathbb{R} \times \mathbb{R}^n \to \mathbb{R}$ is a $C^1$-smooth potential such that $\nabla_q V: \mathbb{R} \times \mathbb{R}^n \to \mathbb{R}^n$ is uniformly bounded in $t$ on every compact subset of $\mathbb{R}^n$, i.e.

\[ \forall \ L > 0 \ \exists \ C > 0 \ \forall \ q \in \mathbb{R}^n \ \forall \ t \in \mathbb{R} \ |q| \leq L \Rightarrow |\nabla_q V(t, q)| \leq C. \]

Suppose that for each $k \in \mathbb{N}$ the boundary value problem

\[ \begin{cases} \dot{q}(t) + \nabla_q V_k(t, q(t)) = f_k(t), \\ q(-k) - q(k) = \dot{q}(-k) - \dot{q}(k) = 0, \end{cases} \]
where \( f_k : \mathbb{R} \to \mathbb{R}^n \) stands for the 2\( k \)-periodic extension of \( f|_{[-k,k]} \) to \( \mathbb{R} \) and \( V_k : \mathbb{R} \times \mathbb{R}^n \to \mathbb{R} \) denotes the 2\( k \)-periodic extension of \( V|_{[-k,k] \times \mathbb{R}^n} \) to \( \mathbb{R} \times \mathbb{R}^n \), has a periodic solution \( q_k \in E_k \) and \( \{ \| q_k \|_{E_k} \}_{k \in \mathbb{N}} \) is a bounded sequence in \( \mathbb{R} \). Then there exists a subsequence \( \{ q_{k_j} \}_{j \in \mathbb{N}} \) converging in the topology of \( C^2_{\text{loc}}(\mathbb{R}, \mathbb{R}^n) \) to a function \( q \in W^{1,2}(\mathbb{R}, \mathbb{R}^n) \) which is a solution of

\[
\ddot{q}(t) + \nabla_q V(t, q(t)) = f(t), \quad t \in \mathbb{R}.
\]

The approximative method was introduced by Paul H. Rabinowitz in [18] for homogenous second order Hamiltonian systems with a time-periodic potential. Later, the second author of this paper extended it to inhomogenous time-periodic Hamiltonian systems (see [10] and [12]), and more recently, Robert Krawczyk generalized it to the case of aperiodic potentials.

Let us now consider for \( k \in \mathbb{N} \) the boundary value problems

\[
\begin{aligned}
\ddot{q}(t) - \nabla_q K_k(t, q(t)) + \nabla_q W_k(t, q(t)) &= f_k(t), \\
\dot{q}(-k) - q(k) &= \dot{q}(-k) - q(k) = 0,
\end{aligned}
\]

where \( f_k : \mathbb{R} \to \mathbb{R}^n \) stands for the 2\( k \)-periodic extension of \( f|_{[-k,k]} \) to \( \mathbb{R} \), and \( K_k : \mathbb{R} \times \mathbb{R}^n \to \mathbb{R} \), \( W_k : \mathbb{R} \times \mathbb{R}^n \to \mathbb{R} \) are the 2\( k \)-periodic extensions of \( K|_{[-k,k] \times \mathbb{R}^n} \) and \( W|_{[-k,k] \times \mathbb{R}^n} \) to \( \mathbb{R} \times \mathbb{R}^n \).

As we have already mentioned in the introduction, our proof consists of two steps. First, we show the existence of solutions of (5), and second, we use Theorem 2.2 to find a solution of (1).

For our first step, let us consider the functionals \( I_k : E_k \to \mathbb{R} \) given by

\[
I_k(q) = \int_{-k}^{k} \left( \frac{1}{2} |\dot{q}(t)|^2 + K_k(t, q(t)) - W_k(t, q(t)) \right) dt + \int_{-k}^{k} (f_k(t), q(t)) dt.
\]

Standard arguments show that \( I_k \in C^1(E_k, \mathbb{R}) \), and

\[
I_k'(q)v = \int_{-k}^{k} \left( \langle \dot{q}(t), \dot{v}(t) \rangle + (\nabla_q K_k(t, q(t)) - \nabla_q W_k(t, q(t)), v(t)) \right) dt + \int_{-k}^{k} (f_k(t), v(t)) dt.
\]

Moreover, the critical points of the functional \( I_k \) are classical 2\( k \)-periodic solutions of (5), and we now show their existence by using the Mountain Pass Theorem. Let us recall the latter result before proceeding with our proof.

**Theorem 2.3** (Mountain Pass Theorem, [2]). Let \( E \) be a real Banach space and \( I : E \to \mathbb{R} \) a \( C^1 \)-smooth functional. If \( I \) satisfies the following conditions:

(i) \( I(0) = 0 \),

(ii) every sequence \( \{ u_j \}_{j \in \mathbb{N}} \) in \( E \) such that \( \{ I(u_j) \}_{j \in \mathbb{N}} \) is bounded in \( \mathbb{R} \) and \( I'(u_j) \to 0 \) in \( E^* \) as \( j \to +\infty \) contains a convergent subsequence (the Palais-Smale condition),

(iii) there exist constants \( \rho, \alpha > 0 \) such that \( I|_{\partial B_\rho(0)} \geq \alpha \),

(iv) there exists \( e \in E \setminus B_\rho(0) \) such that \( I(e) \leq 0 \),

where \( B_\rho(0) \) is the open ball of radius \( \rho \) about 0 in \( E \), then \( I \) possesses a critical value \( c \geq \alpha \) given by

\[
c = \inf_{g \in \Gamma} \max_{s \in [0,1]} I(g(s)),
\]

where

\[
\Gamma = \{ g \in C([0,1], E) : g(0) = 0, \quad g(1) = e \}.
\]

We now denote by \( L^\infty_{2k}(\mathbb{R}, \mathbb{R}^n) \) the space of 2\( k \)-periodic essentially bounded functions from \( \mathbb{R} \) into \( \mathbb{R}^n \) equipped with the norm

\[
\| q \|_{L^\infty_{2k}} = \text{ess sup} \{ |q(t)| : t \in [-k, k] \}.
\]
It is well known that for each $k \in \mathbb{N}$ and $q \in E_k$
\[
\|q\|_{L_{\infty}^{2k}} \leq \sqrt{2}\|q\|_{E_k}.
\] (9)

Furthermore, we will write $L_{2k}^2(\mathbb{R}, \mathbb{R}^n)$ for the Hilbert space of 2k-periodic functions on $\mathbb{R}$ with values in $\mathbb{R}^n$ and with the norm
\[
\|q\|_{L_{2k}^2} = \left( \int_{-k}^{k} |q(t)|^2 dt \right)^{\frac{1}{2}}.
\]

Note that by (2),
\[
\|f_k\|_{L_{2k}^2} < \frac{\sqrt{2}}{4} (b_1 - 2M).
\] (10)

The following lemma shows the existence of a solution of (5) and is the main part of the first step of our proof.

**Lemma 2.4.** For each $k \in \mathbb{N}$, the functional $I_k$ has a critical value of mountain pass type.

**Proof.** We let $k \in \mathbb{N}$ be fixed and note at first that it is evident by $(C_2)$ and $(C_5)$ that $I_k(0) = 0$, which shows (i) in Theorem 2.3.

For checking the Palais-Smale condition (ii), we consider a sequence $\{u_j\}_{j \in \mathbb{N}} \subset E_k$ such that $\{I_k(u_j)\}_{j \in \mathbb{N}}$ is bounded in $\mathbb{R}$ and $I_k'(u_j) \to 0$ in $E_k^*$ as $j \to \infty$. Then there exists a constant $C_k > 0$ such that for all $j \in \mathbb{N}$
\[
|I_k(u_j)| \leq C_k
\] (11)

and
\[
\|I_k'(u_j)\|_{E_k^*} \leq C_k.
\] (12)

Now, we will first show that $\{u_j\}_{j \in \mathbb{N}}$ is bounded in the Hilbert space $E_k$. Using (6) and $(C_5)$ we get
\[
2I_k(u_j) \geq \int_{-k}^{k} (|\dot{u}_j(t)|^2 + 2K_k(t, u_j(t))) dt - \frac{2}{\mu} \int_{-k}^{k} (\nabla_q W_k(t, u_j(t)), u_j(t)) dt
\]
\[+ 2\int_{-k}^{k} (f_k(t), u_j(t)) dt.
\]

From (7) and $(C_3)$ it follows that
\[
I_k'(u_j)u_j \leq \int_{-k}^{k} (|\dot{u}_j(t)|^2 + 2K_k(t, u_j(t))) dt - \int_{-k}^{k} (\nabla_q W_k(t, u_j(t)), u_j(t)) dt
\]
\[+ \int_{-k}^{k} (f_k(t), u_j(t)) dt.
\]

Thus
\[
2I_k(u_j) - \frac{2}{\mu} I_k'(u_j)u_j \geq \left( 1 - \frac{2}{\mu} \right) \int_{-k}^{k} (|\dot{u}_j(t)|^2 + 2K_k(t, u_j(t))) dt
\]
\[+ \left( 2 - \frac{2}{\mu} \right) \int_{-k}^{k} (f_k(t), u_j(t)) dt,
\]

and by $(C_2)$ we have
\[
2I_k(u_j) - \frac{2}{\mu} I_k'(u_j)u_j \geq \left( 1 - \frac{2}{\mu} \right) b_1 \|u_j\|_{E_k}^2 + \left( 2 - \frac{2}{\mu} \right) \int_{-k}^{k} (f_k(t), u_j(t)) dt.
\]
Finally, applying the Hölder inequality, as well as (10), (11) and (12), we obtain
\[
(1 - \frac{2}{\mu}) \bar{b}_1 \|u_j\|_{E_k}^2 = \frac{2C_k}{\mu} \|u_j\|_{E_k}^2 - \frac{\sqrt{2}}{4} (\bar{b}_1 - 2M) \left( 2 - \frac{2}{\mu} \right) \|u_j\|_{E_k} - 2C_k \leq 0.
\]
Since \( \mu > 2 \) we conclude that \( \{u_j\} \) is bounded.

Going to a subsequence if necessary, we can assume that there exists a function \( u \in E_k \) such that \( u_j \rightharpoonup u \) weakly in \( E_k \) as \( j \to +\infty \). Hence \( u_j \to u \) uniformly on \([-k, k]\), which implies that
\[
(I'_k(u_j) - I'_k(u)) (u_j - u) \to 0,
\]
\[
\|u_j - u\|_{L^2_{2k}} \to 0
\]
and
\[
\int_{-k}^{k} (\nabla q K_k(t, u_j(t)) - \nabla q W_k(t, u_j(t)), u_j(t) - u(t))dt
\]
\[
- \int_{-k}^{k} (\nabla q K_k(t, u(t)) - \nabla q W_k(t, u(t)), u_j(t) - u(t))dt \to 0
\]
as \( j \to +\infty \). On the other hand, it is readily seen that
\[
\|\dot{u}_j - \dot{u}\|_{L^2_{2k}}^2 = (I'_k(u_j) - I'_k(u))(u_j - u)
\]
\[
+ \int_{-k}^{k} (\nabla q K_k(t, u_j(t)) - \nabla q W_k(t, u_j(t)), u_j(t) - u(t))dt
\]
\[
- \int_{-k}^{k} (\nabla q K_k(t, u(t)) - \nabla q W_k(t, u(t)), u_j(t) - u(t))dt,
\]
and consequently
\[
\|\dot{u}_j - \dot{u}\|_{L^2_{2k}} \to 0. \quad (14)
\]
By (13) and (14), we see that \( \|u_j - u\|_{E_k} \to 0 \), and thus \( I_k \) satisfies the Palais-Smale condition.

To show (iii), we set
\[
g = \frac{\sqrt{2}}{2}
\]
and assume that \( q \in E_k \) such that \( \|q\|_{E_k} = g \). Note that \( \|q\|_{L^2_{2k}} \leq 1 \) by (9). Thus, we can apply (3) to obtain
\[
\int_{-k}^{k} W(t, q(t))dt \leq \int_{-k}^{k} W \left( t, \frac{q(t)}{|q(t)|} \right) |q(t)|^\mu dt \leq M \int_{-k}^{k} |q(t)|^2 dt \leq M \|q\|^2_{E_k} = \frac{1}{2} M.
\]
From this, (C2) and (2), we get
\[
I_k(q) \geq \frac{1}{2} \bar{b}_1 \|q\|_{E_k}^2 \geq \frac{1}{2} M - \|f_k\|_{L^2_{2k}} \|q\|_{E_k}
\]
\[
\geq \frac{1}{4} (\bar{b}_1 - 2M) - \frac{\sqrt{2}}{2} \|f\|_{L^2}
\]
(15)
\[
= \frac{\sqrt{2}}{2} \left( \frac{\sqrt{2}}{4} (\bar{b}_1 - 2M) - \|f\|_{L^2} \right) \equiv \alpha > 0
\]
To complete the proof, we have to show (iv), i.e. we need to find \( \varepsilon_k \in E_k \) such that \( \|\varepsilon_k\|_{E_k} > \rho \) and \( I_k(\varepsilon_k) \leq 0 \).

Let
In summary, it follows from Theorem 2.3 that the action functional $I_k$ given by

$$I_k(\zeta) = \frac{b_2}{2} \|q\|_{E_k}^2 - m|\zeta|^2 \int_{-k}^k |q(t)|^2 dt + |\zeta| \cdot \|f_k\|_{L^2(E_k)} \|q\|_{E_k} + 2km$$

for all $\zeta \in \mathbb{R} \setminus \{0\}$ and $q \in E_k \setminus \{0\}$.

We now let $Q \in E_1$ be such that $Q \neq 0$ and $Q(-1) = Q(1) = 0$. It follows from (16) that $\|Q\|_{E_1} > \rho$ and $I_1(Q(\zeta)) < 0$ for $\zeta \in \mathbb{R} \setminus \{0\}$ large enough. Hence, if we define $e_1(t) = Q(t)$ and for each $k \geq 2$,

$$e_k(t) = \begin{cases} e_1(t) & \text{for } t \in [-1, 1], \\ 0 & \text{for } t \in [-k, -1) \cup (1, k], \end{cases}$$

then $e_k \in E_k$, and $\|e_k\|_{E_k} = \|e_1\|_{E_1} > \rho$ as well as $I_k(e_k) = I_1(e_1) < 0$.

In summary, it follows from Theorem 2.3 that the action functional $I_k$ has a critical value $c_k \geq \alpha$ given by

$$c_k = \inf_{g \in \Gamma_k} \max_{s \in [0, 1]} I_k(g(s)),$$

where

$$\Gamma_k = \{g \in C([0, 1], E_k) : g(0) = 0, g(1) = e_k\}.$$

\[ \square \]

In what follows, we let $q_k$ be a critical point for the corresponding critical value $c_k$ that we have found in Lemma 2.4. The functions $q_k$, $k \in \mathbb{N}$, are solutions of (5) and as second step of our proof of Theorem 1.1, we now want to apply Theorem 2.2 to this sequence of functions.

**Lemma 2.5.** The sequence $\{\|q_k\|_{E_k}\}_{k \in \mathbb{N}} \subset \mathbb{R}$ is bounded.

**Proof.** We set

$$M_0 = \max_{s \in [0, 1]} I_1(se_1).$$

and conclude from (17) and (18) that

$$c_k \leq M_0$$

for each $k \in \mathbb{N}$. By assumption,

$$c_k = I_k(q_k) = I_k(q_k) - \frac{1}{2} I_k'(q_k)q_k = \int_{-k}^k K_k(t, q_k(t)) + \frac{1}{2} (\nabla_q K_k(t, q_k(t)), q_k(t)) dt \ + \int_{-k}^k \frac{1}{2} (\nabla_q W_k(t, q_k(t)), q_k(t)) - W_k(t, q_k(t)) dt + \frac{1}{2} \int_{-k}^k (f_k(t), q_k(t)) dt.$$

Applying $(C_3)$ and $(C_5)$ we obtain

$$c_k \geq \left(\frac{\mu}{2} - 1\right) \int_{-k}^k W_k(t, q_k(t)) dt + \frac{1}{2} \int_{-k}^k (f_k(t), q_k(t)) dt.$$

Furthermore, it follows from (6) and $(C_2)$ that

$$\int_{-k}^k W_k(t, q_k(t)) dt \geq \frac{1}{2} b_1 \|q_k\|_{E_k}^2 + \int_{-k}^k (f_k(t), q_k(t)) dt - I_k(q_k).$$

Using that $I_k(q_k) = c_k$, the previous two inequalities give

$$\frac{1}{2} b_1 \|q_k\|_{E_k}^2 - \frac{\mu - 1}{\mu - 2} \|f_k\|_{L^2(E_k)} \|q_k\|_{E_k} - \frac{\mu}{\mu - 2} c_k \leq 0,$$

7
which implies by (2) and (19) that
\[
\frac{1}{2} \hat{b}_1 \|q_k\|_{E_k} - \frac{\sqrt{2}}{4} (\hat{b}_1 - 2M) \frac{\mu - 1}{\mu - 2} \|q_k\|_{E_k} - \frac{\mu}{\mu - 2} M_0 \leq 0.
\]
Hence there is \( M_1 > 0 \) such that for each \( k \in \mathbb{N} \),
\[
\|q_k\|_{E_k} \leq M_1.
\]

Now, using Theorem 2.2 we see that there exists a solution \( q: \mathbb{R} \rightarrow \mathbb{R}^n \) of (1) such that \( q(t) \to 0 \) as \( |t| \to \infty \).

All what is left to show for the proof of Theorem 1.1 is that actually \( \dot{q}(t) \to 0 \) as \( |t| \to \infty \). This, however, follows from the inequality
\[
|\dot{q}(t)| \leq \sqrt{2} \left( \int_{t - \frac{1}{2}}^{t + \frac{1}{2}} (|\dot{q}(s)|^2 + |\ddot{q}(s)|^2) \, ds \right)^{\frac{1}{2}}, \quad t \in \mathbb{R},
\]
which can be found in [10] (Inequality (28), p. 385). Indeed, we just need to note that by (1), \((C_2),(C_4)\) and (2)
\[
\int_{t - \frac{1}{2}}^{t + \frac{1}{2}} |\ddot{q}(s)|^2 \, ds \to 0, \quad |t| \to \infty.
\]
If now \( |t| \) goes to \( \infty \) in (20) we see that \( |\dot{q}(t)| \to 0 \) as \( |t| \to \infty \). Consequently, \( q \) is a solution of (1) and the proof of Theorem 1.1 is complete.

3 One-dimensional Examples

In this section we present examples for \( n = 1 \) satisfying the assumptions of Theorem 1.1, and the graphs of their approximating solutions \( q_k \) of (5) for increasing values of \( k \).

Example 3.1. Consider \( K: \mathbb{R} \times \mathbb{R} \to \mathbb{R}, W: \mathbb{R} \times \mathbb{R} \to \mathbb{R} \) and \( f: \mathbb{R} \to \mathbb{R} \) given by
\[
K(t, q) = t^2 + \frac{1}{t^2 + 2} q^2,
\]
\[
W(t, q) = \frac{1}{3} t^2 + 12 q^4
\]
and
\[
f(t) = \frac{1}{36} e^{-t^2},
\]
where \( t, q \in \mathbb{R} \). One can easily check that \( K, W \) and \( f \) satisfy the assumptions of Theorem 1.1.

Example 3.2. Let \( K: \mathbb{R} \times \mathbb{R} \to \mathbb{R}, W: \mathbb{R} \times \mathbb{R} \to \mathbb{R} \) and \( f: \mathbb{R} \to \mathbb{R} \) be given by
\[
K(t, q) = \left( \frac{1}{8} \sin(t) + \frac{1}{8} \sin(\sqrt{2}t) + \frac{3}{4} \right) q^2,
\]
\[
W(t, q) = \frac{1}{4} q^4
\]
and
\[
f(t) = \frac{1}{32} e^{-t^2},
\]
where \( t, q \in \mathbb{R} \). It is immediate that \( K, W \) and \( f \) satisfy the assumptions of Theorem 1.1.
Example 3.3. Consider $K: \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$, $W: \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$ and $f: \mathbb{R} \rightarrow \mathbb{R}$ given by

$$K(t, q) = q^2,$$

$$W(t, q) = \frac{10}{33} t^4 \left( \arctan \left( \frac{q^2}{t^2 + 1} \right) + 1 \right)$$

and

$$f(t) = \frac{1 + t^2}{10} e^{-t^2},$$

where $t, q \in \mathbb{R}$. Again, it is readily seen that $K, W$ and $f$ satisfy the assumptions of Theorem 1.1.

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References


