A KANTOROVICH-TYPE CONVERGENCE ANALYSIS FOR THE QUASI-GAUSS-NEWTON METHOD

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ABSTRACT. The convergence properties of Quasi-Gauss-Newton methods for nonlinear equations described by Wang [Comp. & Math. with Applic., 25, No 1, 53-63 (1993)] are investigated. The superlinear convergence and a Kantorovich-type convergence analysis of the methods is proved and the superlinear convergence is shown.

1. Introduction

We consider numerical methods for finding a solution to a nonlinear system of algebraic equations

\[ f(x) = 0, \]

where the function \( f: \mathbb{R}^n \rightarrow \mathbb{R}^n \) is in \( x \in \mathbb{R}^n \). In [10], a quasi-Gauss-Newton method is proposed and shown the computational efficiency over SQRT algorithm by numerical experiments. The convergence rate of the method has not been proved theoretically. In this paper, we show theoretically that the iterate \( x_k \) obtained from the quasi-Gauss-Newton method for the problem (1) actually converges to a root by Kantorovich-type convergence analysis. We also show the rate of convergence of the method is superlinear.

Since the quasi-Gauss-Newton method is a modified Gauss-Newton method, we first discuss Gauss-Newton method briefly. Gauss-Newton method solves

\[ J(x)^T J(x)s = -J(x)^T f(x), \]

where \( J(x) \) is the Jacobian of \( f \) at \( x \), for \( s \) at each iteration to have a better approximation to a solution. The equation (2) is usually computed by \( QR \)
decomposition of $J(x)$. If we use an approximation $B$ for $J(x)$, then (2) becomes

\begin{equation}
B^T B s = -B^T f(x).
\end{equation}

One of the most successful approximations for $J(x)$ is Broyden’s update [1]. Wang showed in [10] that using $LDL^T$ factorization of $B^T B$ leads to superior computational results than the $SQRT$ method for a given set of test problems and using the modified Cholesky factorization in [6] reduces the number of operations from $O(n^3)$ to $O(n^2) + n$.

It is essential to give convergence analysis for the numerical methods that are developed. Such convergence analysis of other methods for systems of nonlinear equations can be found in [2, 3, 8, 7, 5, 9]. In following sections, we first describe Quasi-Gauss-Newton method. And then, we show the method is convergent to a root and its convergence rate is superlinear. It is followed by a Kantorovich-type analysis for the method.

2. Quasi-Gauss-Newton method

In this section, we describe the quasi-Gauss-Newton method in [10] with the modified Cholesky factorization in [6] to solve (3).

The method uses an algorithm in [6] given as Algorithm 2.1 in this section. It modifies a symmetric matrix $A$ by a symmetric matrix of rank one,

\begin{equation}
\overline{A} = A + \alpha zz^T
\end{equation}

and finds the Cholesky factors of $\overline{A} = LDL^T$ from the factors of $A = LDL^T$. If $B^T B$ is modified by a rank-one update as in (4), then the updated matrix $\overline{B^T B}$ can be obtained as follows.

\begin{equation}
\overline{B^T B} = B^T B + \alpha zz^T = L(D + \alpha pp^T)L^T,
\end{equation}

where $Lp = z$, and $p$ is obtained from $z$. If we factor

\begin{equation}
D + \alpha pp^T = \tilde{L}\tilde{D}\tilde{L}^T,
\end{equation}

the required modified Cholesky factors are of the form,

\begin{equation}
\overline{B^T B} = \tilde{L}\tilde{D}\tilde{L}^T L^T.
\end{equation}
Therefore,
\[ L = L\tilde{L}, \quad D = \tilde{D}. \]

Initially, we need the orthogonal factorization of \( B \) to have \( B^T B = R^T R \). Then, the initial \( L \) and \( D \) can be obtained from \( R^T R \). The algorithm for updating \( L \) and \( D \) is:

**Algorithm 2.1** [6]

Define \( \alpha_1 = \alpha, \ w^{(1)} = z \).

Do for \( j = 1, \ldots, n \):

- \( p_j = w^{(j)} \)
- \( \overline{d}_j = d_j + \alpha_j p_j^2 \)
- \( \beta_j = p_j \alpha_j / \overline{d}_j \)
- \( \alpha_{j+1} = d_j \alpha_j / \overline{d}_j \)

Do for \( r = j + 1, \ldots, n \):

- \( w_r^{(j+1)} = w_r^{(j)} - p_j l_{rj} \)
- \( l_{rj} = l_{rj} + \beta_j w_r^{(j+1)} \)

If \( \overline{B} = B + \frac{Ts}{s^Ts} \) is used in (5),

\[ \overline{B}^T \overline{B} = B^T B + B^T \frac{fs^T}{s^Ts} + \frac{s^T}{s^Ts} B + \frac{s^T}{s^Ts} s^T. \]

From the above equation, we can see that \( B^T B \) is modified by a rank-2 update and (6) can be rewritten as

\[ \overline{B}^T \overline{B} = B^T B + z_1 z_1^T - z_2 z_2^T, \]

where \( z_1 = [B^T \overline{f} + (1 - \overline{f}^T \overline{f} / 2) \frac{s^T}{s^Ts}] / \sqrt{2} \) and \( z_2 = [B^T \overline{f} - (1 + \overline{f}^T \overline{f} / 2) \frac{s^T}{s^Ts}] / \sqrt{2} \).

The algorithm for Quasi-Gauss-Newton method [10] using Broyden’s update is:
Algorithm 2.2

Given \( f : R^n \to R^n, x_0 \in R^n, B_0 \in R^{n \times n} \).

Get \( Q_0 R_0 = B_0 \)

\( L_0 \) from \( R^T \)

\( D_0 = (r_{11}^2, \ldots, r_{nn}^2) \).

Do for \( k = 1, \ldots : \)

Solve \( L_k D_k L_k^T s_k = -B_k^T f(x_k) \) for \( s_k \), \( x_{k+1} := x_k + s_k \), \( y_k := f(x_{k+1}) - f(x_k) \), \( t_k := -B_k^T f(x_k) \), \( B_{k+1} := B_k + \frac{(y_k - B_k s_k)s_k^T}{s_k^T s_k} \).

Get \( LDL^T \) by Algorithm 2.1.

In the next section, we will give a convergence analysis of Algorithm 2.2.

3. Superlinear Convergence of QGN

In this section, we show that the method by (6) is well defined and converges to a solution of (1). We start with the bound deterioration theorem of the method.

**Theorem 3.1. (The Bounded Deterioration Theorem)** Let \( D \subseteq R^n \) be an open convex set containing \( x_k, x_{k+1} \), with \( x_k \neq x_\ast \). Let \( f : R^n \to R^n, B_k \in R^{n \times n} \), and

\[
B_{k+1}^T B_{k+1} = B_k^T B_k + B_k^T \frac{f_{k+1} s^T}{s^T s} + B_k \frac{s f_{k+1}^T}{s^T s} + \frac{s f_{k+1}^T}{s^T s} f_{k+1} s^T.
\]

If \( x_\ast \in D \) and \( J(x) \) obeys the weaker Lipschitz condition,

\[
\| J(x) - J(x_\ast) \| \leq \gamma \| x - x_\ast \|, \quad \text{for all } x \in D,
\]
then, for both the Frobenius and $l_2$ matrix norms,

$$
\|(B_{k+1} - J(x_*))^T (B_{k+1} - J(x_*)\| \\
\leq \|[B_k - J(x_*)] + \gamma \|x_{k+1} - x_*\|_2 + \|x_k - x_*\|_2\|^2.
$$

Proof. Let $J_* \equiv J(x_*)$. Adding $-J_*^T B_{k+1} - B_{k+1}^T J_* + J_*^T J_*$ to the both sides of (7), we get

$$
B_{k+1}^T B_{k+1} - J_*^T B_{k+1} - B_{k+1}^T J_* + J_*^T J_* + B_k^T \frac{(y - B_k s)s^T}{s^T s}
$$

$$
= B_k^T B_k - J_*^T B_{k+1} - B_{k+1}^T J_* + J_*^T J_* + B_k^T \frac{(y - B_k s)s^T}{s^T s}
$$

$$
+ \frac{s(y - B_k s)^T s^T}{s^T s} B_k + \frac{s(y - B_k s)^T (y - B_k s)s^T}{s^T s}
$$

$$
= \left[ B_k - J_* + \frac{(y - B_k s)s^T}{s^T s} \right]^T \left[ B_k - J_* + \frac{(y - B_k s)s^T}{s^T s} \right]
$$

$$
= \left[ (B_k - J_*) \left[ I - \frac{ss^T}{s^T s} \right] + \frac{(y - J_* s)s^T}{s^T s} \right]^T \left[ (B_k - J_*) \left[ I - \frac{ss^T}{s^T s} \right] + \frac{(y - J_* s)s^T}{s^T s} \right].
$$

Then, it follows that

$$
\|(B_{k+1} - J_*)^T (B_{k+1} - J_*)\| \leq \left\| (B_k - J_*) \left[ I - \frac{ss^T}{s^T s} \right] \right\| + \frac{\|y - J_* s\|_2}{\|s\|_2}^2.
$$

Using

$$
\left\| I - \frac{ss^T}{s^T s} \right\|_2 = 1,
$$

and

$$
\|y - J_* s\|_2 \leq \frac{\gamma}{2} (\|x_{k+1} - x_*\|_2 + \|x_k - x_*\|_2) \|s\|_2
$$

in [4], we have (8).
THEOREM 3.2. (Linear Convergence Theorem) Let all the assumptions of Theorem 3.1 hold. Suppose that \( \| J(x_\ast)^{-1} \| \leq \beta \) and, for arbitrary \( \epsilon \) and \( \delta > 0 \) we can choose \( x_0 \) and \( B_0 \) such that \( \| x_0 - x_\ast \| < \epsilon \) and \( \| B_0 - J(x_\ast) \| < \delta \). If \( B_k^T B_k \) satisfy

\[
\| (B_{k+1} - J(x_\ast))^T (B_{k+1} - J(x_\ast)) \| \\
\leq \left[ \| B_k - J(x_\ast) \| + \frac{\gamma}{2} (\| x_{k+1} - x_\ast \| + \| x_k - x_\ast \|) \right]^2,
\]

then \( x_k \) converges at least linearly to \( x_\ast \).

Proof. We will show that by induction, for \( k = 0, 1, 2, \ldots \),

\[
\| (B_k - J_\ast)^T (B_k - J_\ast) \| \leq [(2 - 2^{-k}) \delta]^2
\]

and

\[
\| e_{k+1} \| \leq \frac{\| e_k \|}{2}.
\]

Choose \( \epsilon \) and \( \delta \) such that

\[
7\beta \delta \leq 1 \quad \text{and} \quad 3\gamma \epsilon \leq 2\delta.
\]

When \( k = 0 \),

\[
\| (B_0 - J_\ast)^T (B_0 - J_\ast) \| \leq \| (B_0 - J_\ast) \| \| (B_0 - J_\ast) \| \leq \delta^2,
\]

by assumption. To show that \( \| e_1 \| \leq \frac{\| e_0 \|}{2} \), we consider the following equation from the iteration,

\[
B_0^T B_0 (x_1 - x_0) = -B_0^T f_0.
\]

Hence,

\[
e_1 = e_0 + (B_0^T B_0)^{-1} (-B_0^T f_0) \\
= e_0 + B_0^{-1} (-f_0 + f_\ast + J_\ast e_0) - B_0^{-1} J_\ast e_0.
\]

In \( \| \cdot \| \),

\[
\| e_1 \| \leq \| B_0^{-1} \| \| -f_0 + f_\ast + J_\ast e_0 \| + \| B_0 - J_\ast \| \| e_0 \| \|. 
\]
If $\|J(x)_{-1}\| \leq \beta$, using Theorem 3.1.4 in [4], it can be shown that

$$\|B_k^{-1}\| \leq \frac{3}{2} \beta.$$  
\(\text{(14)}\)

$$\|e_1\| \leq \frac{3}{2} \beta \left[ \frac{\gamma}{2} \|e_0\| + \delta \right]\|e_0\|.$$  

Since

$$\frac{\gamma\|e_0\|}{2} \leq \frac{\gamma \varepsilon}{2} \leq \frac{\delta}{3},$$

the inequality (14) becomes

$$\|e_1\| \leq \frac{3}{2} \beta \left[ \frac{\delta}{3} + 2\delta \right] \|e_0\|$$

$$\leq 3\beta\delta\|e_0\|$$

$$\leq \frac{\|e_0\|}{2}.$$  

For $k = 0, 1, \ldots, i - 1$, let us assume that (11) and (12) hold. Then, for $k = i$, using

$$\|e_i\| \leq \frac{1}{2}\|e_{i-1}\|,$$

$$\|e_{i-1}\| \leq 2^{-(i-1)}\epsilon,$$  

(12), and Theroem 3.1,

$$\|(B_i - J_{x})^T (B_i - J_{x})\| \leq [(2 - 2^{-(i-1)})\delta + \frac{\gamma}{2}\|e_{i-1}\| + \|e_i\|]^2$$

$$\leq [(2 - 2^{-(i-1)})\delta + \frac{3}{4}\gamma\|e_{i-1}\|]^2$$

$$\leq [(2 - 2^{-i})\delta]^2.$$  
\(\text{(15)}\)

We omit the proof of (12) since it is identical to the proof of the initial step of the induction.

**Theorem 3.4.** (Superlinear Convergence) Let all the assumptions of Theorem 3.1 hold. Then, the sequence \{\(x_k\)\} generated by Algorithm 2.2 is well defined and converges superlinearly to \(x_\ast\).
Proof. Define \( E_k = B_k - J_* \), and let \( \| \cdot \| \) denote the \( l_2 \) vector norm. From (9),

\[
\| E_{k+1}^T E_{k+1} \|_F \leq \| (I - \frac{s_k s_k^T}{s_k^T s_k}) E_k^T E_k (I - \frac{s_k s_k^T}{s_k^T s_k}) \|_F
\]

\[
+ 2 \| E_k (I - \frac{s_k s_k^T}{s_k^T s_k}) \|_F \frac{\| y_k - J_* s_k \|_2}{\| s_k \|_2} + \left( \frac{\| y_k - J_* s_k \|_2}{\| s_k \|_2} \right)^2.
\]

Using \( \frac{\| y - J_* s_k \|_2}{\| s_k \|_2} \leq \frac{\gamma}{4} (\| e_k \|_2 + \| e_{k+1} \|_2) \) in the proof of Theorem 3.1 and \( \| e_{k+1} \| \leq \frac{1}{2} \| e_k \| \), we have

(17)

\[
\frac{\| y - J_* s_k \|_2}{\| s_k \|_2} \leq \frac{3 \gamma}{4} \| e_k \|_2.
\]

In view of Lemma 3.3 and (17),

\[
\| E_{k+1}^T E_{k+1} \|_F \leq \| E_k^T E_k \|_F - \frac{1}{2 \| E_k^T E_k \|_F} \| E_k^T E_k s_k \|_2^2
\]

\[
+ \frac{3 \gamma \| E_k \|_F}{2} \| e_k \| + \frac{9 \gamma^2}{16} \| e_k \|_2^2.
\]

This can be rewritten as

\[
\frac{\| E_k^T E_k s_k \|_2^2}{\| s_k \|_2^2} \leq 2 \| E_k^T E_k \|_F \| E_k^T E_k \|_F - \| E_{k+1}^T E_{k+1} \|_F
\]

\[
+ \frac{3 \gamma}{2} \| E_k \|_F \| e_k \| + \frac{9 \gamma^2}{16} \| e_k \|_2^2.\]

From Theorem 3.2, \( \| E_k^T E_k \|_F \leq 4 \delta^2 \) and \( \| E_k \| \leq 2 \delta \) for all \( k \geq 0 \), \( \sum_{k=0}^\infty \| e_k \| \leq 2 \epsilon \), and \( \sum_{k=0}^\infty \| e_k \|_2^2 \leq \frac{4}{3} \epsilon \),

\[
\frac{\| E_k^T E_k s_k \|_2^2}{\| s_k \|_2^2} \leq 4 \delta^2 \| E_k^T E_k \|_F - \| E_{k+1}^T E_{k+1} \|_F + 3 \delta \gamma \| e_k \| + \frac{9 \gamma^2}{16} \| e_k \|_2^2.
\]
4. A Kantorovich-type Analysis of QGN

**Theorem 4.1.** Let all the assumptions of Theorem 3.1 hold. Then,

\[ \| B(x_k) - J(x_k) \|_F \leq \| B(x_0) - J(x_0) \|_F + \frac{3}{2} y \sum_{j=1}^{k} \| x_j - x_{j-1} \|_2. \]

**Proof.** Using Lemma 8.2.1 in [4],

\[ \| B_k - J_k \|_F \leq \| B_{k-1} - J_{k-1} \|_F + \frac{3}{2} y \| x_k - x_{k-1} \| \]

\[ \leq \| B_0 - J_0 \|_F + \frac{3}{2} y \sum_{j=1}^{k} \| x_j - x_{j-1} \|. \]

We now present the Kantorovich-type analysis for the Quasi-Gauss-Newton method. Let us define \( S(y, \delta) = \{ x \in \mathbb{R}^n \mid \| x - y \| < \delta, y \in \mathbb{R}^n \} \) and \( \overline{S}(y, \delta) \) the closure of \( S(y, \delta) \).
THEOREM 4.2. Let all the assumptions of Theorem 3.1 hold and $B_k$ be nonsingular. Assume that $\delta$, $\beta$ and $\eta$ are positive scalars such that $\|B_0 - J_0\|_F \leq \delta$,$\|B_0^{-1}\|_F \leq \beta$, $\|B_0^{-1}f(x_0)\| \leq \eta$,
\[
h = \frac{\beta \gamma \eta}{(1 - 3\beta \delta)^2} \leq \frac{1}{9},
\]
and $\beta \delta < 1/3$. If $S(x_0, t_a) \subset D$, where
\[
t_a = \frac{2}{9\beta \gamma} (1 - 3\beta \delta)(1 - \sqrt{1 - 9h}),
\]
then $x_k$ by algorithm 2.2 is well-defined, remains in $S(x_0, t_a)$ and converges to $x_*$.

Proof. Let
\[
f(t) = \frac{9}{4} \gamma t^2 - \left(\frac{1 - 3\beta \delta}{\beta}\right)t + \frac{\eta}{\beta}.
\]
Consider the iteration,
\[
t_{k+1} - t_k = \beta f(t_k),
\]
where $t_0 = 0$, $k = 0, 1, 2,...$ Then, $f(t_{k-1}) = 1/\beta(t_k - t_{k-1})$. Taylor series expansion of $f$ yields
\[
f(t_k) = f(t_{k-1}) + f'(t_{k-1})(t_k - t_{k-1}) + \frac{1}{2} f''(t_{k-1})(t_k - t_{k-1})^2.
\]
In view of (18) and (20),
\[
f(t_k) = 3\left[\frac{3}{4} \gamma (t_k - t_{k-1}) + \frac{3}{2} \gamma t_{k-1} + \delta\right](t_k - t_{k-1}).
\]
Substituting (21) into (19),
\[
t_{k+1} - t_k = 3\beta \left[\frac{3}{4} \gamma (t_k - t_{k-1}) + \frac{3}{2} \gamma t_{k-1} + \delta\right](t_k - t_{k-1})
\]
\[
= 3\beta \left[\frac{3}{4} \gamma (t_k + t_{k-1}) + \delta\right](t_k - t_{k-1}).
\]
By induction, we can show that \( t_k \) is a strictly increasing sequence. Next, we show that \( t_k \leq t_* \). Using the fact that \( t_* \) is a root of \( f(t) \),

\[
t_* - t_{k+1} = t_* - t_k - \beta f(t_k)
\]

\[
= \beta \left\{ \frac{1}{\beta} (t_* - t_k) - f(t_k) \right\}
\]

\[
= \beta \left\{ [f(t_*) - f(t_k) - f'(t_k)(t_* - t_k)] + [f'(t_k) + \frac{1}{\beta}](t_* - t_k) \right\}.
\]

By (19) and (20),

\[
t_* - t_{k+1} = \beta \left\{ \frac{1}{2} f''(t_k)(t_* - t_k)^2 + [f'(t_k) + \frac{1}{\beta}](t_* - t_k) \right\}
\]

\[
= \beta \left\{ \frac{9}{4} \gamma (t_* - t_k) + \frac{9}{2} \gamma t_k + 3 \delta \right\} (t_* - t_k)
\]

\[
= \beta \left\{ \frac{9}{4} \gamma (t_* + t_k) + 3 \delta \right\} (t_* - t_k).
\]

Since \( t_0 = 0 \) and \( t_* > 0 \), we have

\[
t_k \leq t_*, \quad k = 0, 1, 2, ...
\]

Therefore, there exists a \( \tilde{t} \leq t_* \) such that

\[
\lim_{k \to \infty} t_k = \tilde{t}.
\]

Using (19) and (24), we have \( f(\tilde{t}) = 0 \), hence, \( \tilde{t} = t_* \) since \( t_* \) is the smallest root of \( f \). We have shown that \( \lim_{t \to \infty} = t_* \).

We prove the followings by induction on \( k \):

\[
\{x_k\} \subset \mathcal{S}(x_0, t_*),
\]

\[
\|B_k^{-1}\|_F \leq 3 \beta, \quad k = 1, 2, ...
\]

and

\[
\|x_{k+1} - x_k\| \leq t_{k+1} - t_k, \quad k = 1, 2, ...
\]
When \( k = 0 \),
\[
\|x_1 - x_0\| = \eta = t_1 - t_0 \leq t_s,
\]
from \( t_0 = 0 \) and (23). Suppose that (25) hold for \( k = 0, 1, \ldots, i - 1 \). Then,
\[
\|x_k - x_0\| \leq \sum_{i=0}^{k-1} \|x_{i+1} - x_i\| \leq \sum_{i=0}^{k-1} (t_{i+1} - t_i) = t_k \leq t_s.
\]
This implies \( x_k \in \mathcal{S}(x_0, t_s) \). To show (26), we use Theorem 4.1,
\[
\|B_k - J_k\|_F \leq \|B_0 - J_0\|_F + \frac{3}{2} \gamma \sum_{i=1}^{k} \|x_i - x_{i-1}\|,
\]
for all \( k \), and
\[
\frac{5}{2} \gamma t_s + 2\delta \leq \frac{2}{3} \beta.
\]
Now, we can proceed as follows:
\[
\|B_0^{-1}(B_k - B_0)\|_F
\leq \|B_0^{-1}\|_F \left( \|B_k - J_k\|_F + \|J_k - J_0\|_F + \|J_0 - B_0\|_F \right)
\leq \beta(2\delta + \frac{3}{2} \gamma \sum_{i=1}^{k} \|x_i - x_{i-1}\| + \gamma \|x_k - x_0\|)
\leq \beta(2\delta + \frac{5}{2} \gamma t_k)
\leq \beta(2\delta + \frac{5}{2} \gamma t_s)
\leq \frac{2}{3} \beta.
\]
Therefore,
\[
\|B_k^{-1}\|_F \leq \frac{\beta}{1 - 2/3} = 3\beta.
\]
A Kantorovich-type convergence analysis

by Lemma 2.3.2 in [9]. It remains to show (27). Since

\[ B_{k-1}^T B_{k-1} (x_k - x_{k-1}) + B_{k-1}^T f_{k-1} = 0 \]

is equivalent to

\[ B_{k-1} (x_k - x_{k-1}) + f_{k-1} = 0, \]

\[
\|x_{k+1} - x_k\| \leq \|B_k^{-1}\| F \|f_k\|
\]

\[
= \|B_k^{-1}\| F \|f_k - f_{k-1} - B_{k-1} (x_k - x_{k-1})\|
\]

\[
\leq \|B_k^{-1}\| F (\|f_k - f_{k-1} - J_{k-1} (x_k - x_{k-1})\|
+ \|(J_{k-1} - B_{k-1}) (x_k - x_{k-1})\|).
\]

By (26), Lemma 4.1.12 in [4], (27), and (22),

\[
\|x_{k+1} - x_k\|
\leq 3\beta \left\{ \frac{\gamma}{2} \|x_k - x_{k-1}\| + \frac{3}{2} \frac{\gamma}{2} \sum_{i=0}^{k-2} \|x_{i+1} - x_i\| + \delta \right\}\|x_k - x_{k-1}\|
\]

\[
\leq 3\beta \left\{ \frac{\gamma}{2} (t_k - t_{k-1}) + \frac{3}{2} \frac{\gamma}{2} t_{k-1} + \delta \right\}(t_k - t_{k-1})
\]

\[
\leq 3\beta \left\{ \frac{3}{4} \frac{\gamma}{2} (t_k - t_{k-1}) + \frac{3}{2} \frac{\gamma}{2} t_{k-1} + \delta \right\}(t_k - t_{k-1})
\]

\[
\leq 3\beta \left\{ \frac{3}{4} \frac{\gamma}{2} (t_k + t_{k-1}) + \delta \right\}(t_k - t_{k-1})
\]

\[= t_{k+1} - t_k. \]

This shows that there is an \(x_* \in D\) such that \(\lim_{k \to \infty} x_k = x_*\).

References


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