A Proof of Theorem 5.3

In this section we present the main proof to Theorem 5.3. We define $\boldsymbol{\epsilon}_t = \mathbf{d}_t - \nabla F(\mathbf{x}_t)$ for simplicity.

To prove the main theorem, we need two groups of lemmas to charctrize the behavior of the Algorithm `Pullback-STORM`.

Next lemma provides the upper bound of $\boldsymbol{\epsilon}_t$.

Lemma A.1. Set $\eta \leq \sigma/(2bL)$, $r \leq \sigma/(2bL)$ and $\overline{D} \leq \sigma^2/(4b^2L^2)$, $a = 56^2\log(4/\delta)/b$, $B = b^2$,$a \leq 1/4\ell_{\text{thres}}$, with probability at least $1-2\delta$, for all t we have

$$\|\boldsymbol{\epsilon}_t\|_2 \leq \frac{2^{10}\log(4/\delta)\sigma}{b}.$$

Furthermore, by the choice of b in Theorem 5.1 we have that $\|\boldsymbol{\epsilon}_t\|_2 \leq \epsilon/2$.

Proof. See Appendix B.1. □

Lemma A.2. Suppose the event in Lemma A.1 holds and $\eta \leq \epsilon/(2L)$, then for any s, we have

$$F(\mathbf{x}_{t_s}) - F(\mathbf{x}_{m_s}) \geq \frac{(m_s - t_s)\eta\epsilon}{8}.$$

Proof. The proof is the same as that of Lemma 6.2, with the fact $\|\boldsymbol{\epsilon}_t\|_2 \leq \epsilon/2$ from Lemma A.1. □

The choice of η in Theorem 5.3 further implies that the loss decrease by $\sigma\epsilon/(16bL)$ on average.

Next lemma shows that if $\mathbf{x}_{m_s}$ is a saddle point, then with high probability, the algorithm will break during the Escape phase and set FIND←false. Thus, whenever $\mathbf{x}_{m_s}$ is not a local minimum, the algorithm cannot terminate.

Lemma A.3. Under Assumptions 3.1 and 3.2, set $r \leq L\eta_H\epsilon_H/\rho$, $a \leq \eta_H\epsilon_H$, $b \geq \max\{16\log(4/\delta)\eta_H^{-2}L^{-2}\epsilon_H^{-2}, 56^2\log(4/\delta)a^{-1}\}$,$\ell_{\text{thres}} = 2\log(8\epsilon_H\sqrt{d}\rho^{-1}\delta^{-1}r^{-1})/(\eta_H\epsilon_H)$, $\eta_H \leq \min\{1/(10L\log(8\epsilon_H L\rho^{-1}r_0^{-1})), 1/(10L\log(\ell_{\text{thres}}))\}$ and $\overline{D} < L^2\eta_H^2\epsilon_H^2/(\rho\ell_{\text{thres}}^2)$. Then for any s, when $\lambda_{\min}(\nabla^2 F(\mathbf{x}_{m_s})) \leq -\epsilon_H$, with probability at least $1-2\delta$ algorithm breaks in the Escape phase.

Proof. See Appendix B.2. □

Next lemma shows that `Pullback-STORM` decreases when it breaks.

Lemma A.4 (localization)**.** Suppose the event in Lemma A.1 holds, and $r \leq \min\left\{\log(4/\delta)^2\eta_H\sigma^2/(4b^2\epsilon), \sqrt{2\log(4/\delta)^2\eta_H\sigma^2/(b^2L)}\right\}$, $\eta_H \leq 1/\big(2^{12}L\log(4/\delta)\big)$, $\overline{D} = \sigma^2/(4b^2L^2)$. Then for any s, when `Pullback-STORM` breaks, then $\mathbf{x}_{m_s}$ satisfies

$$F(\mathbf{x}_{m_s}) - F(\mathbf{x}_{t_{s+1}}) \geq (t_{s+1} - m_s)\frac{\log(4/\delta)^2\eta_H\sigma^2}{b^2}. \tag{A.1}$$

Proof. See Appendix B.3. □

With all above lemmas, we prove Theorem 5.3.

Proof of Theorem 5.3. Under the choice of parameter in Theorem 5.3, we have Lemma A.1 to A.4 hold. Now for GD phase, we know that the function value F decreases by $\sigma\epsilon/(16bL)$ on average. For Escape phase, we know that the F decreases by $\log(4/\delta)^2\eta_H\sigma^2/b^2$ on average. So `Pullback-STORM` can find (ϵ, ϵ_H)-approximate local minima within $\widetilde{O}(bL\Delta\sigma^{-1}\epsilon^{-1} + b^2L\Delta\sigma^{-2})$ iterations (we use the fact that $\eta_H = \widetilde{O}(L^{-1})$). Then the total number of stochastic gradient evaluations is bounded by $\widetilde{O}(B + b^2L\Delta\sigma^{-1}\epsilon^{-1} + b^3L\Delta\sigma^{-2})$. Plugging in the choice of $b = \widetilde{O}(\sigma\epsilon^{-1} + \sigma\rho\epsilon_H^{-2})$ in Theorem 5.3, we have the total sample complexity

$$\widetilde{O}\bigg(\frac{\sigma L\Delta}{\epsilon^3} + \frac{\sigma\rho^2 L\Delta}{\epsilon\epsilon_H^4} + \frac{\sigma\rho^3 L\Delta}{\epsilon_H^6}\bigg).$$

The proof finishes by using Young's inequality. □

B Proof of Lemmas in Section A

In this section we prove lemmas in Section A. Let filtration $\mathcal{F}_{t,b}$ denote the all history before sample $\boldsymbol{\xi}_{t,b}$ at time $t \in \{0, \cdots, T\}$, then it is obvious that $\mathcal{F}_{0,1} \subseteq \mathcal{F}_{0,b} \subseteq \cdots \subseteq \mathcal{F}_{1,1} \subseteq \cdots \subseteq \mathcal{F}_{T,1} \subseteq \cdots \subseteq \mathcal{F}_{T,b}$.

We also need the following fact:

Proposition B.1. For any t, we have the following equation:

$$\frac{\boldsymbol{\epsilon}_{t+1}}{(1-a)^{t+1}} - \frac{\boldsymbol{\epsilon}_t}{(1-a)^t} = \frac{1}{(1-a)^{t+1}} \sum_{i \le b} \boldsymbol{\epsilon}_{t,i},$$

where

$$\begin{aligned}\boldsymbol{\epsilon}_{t,i} &= \frac{a}{b}[\nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1})] \\ &\quad + \frac{1-a}{b}[\nabla F(\mathbf{x}_t) - \nabla f(\mathbf{x}_t; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1}) + \nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i)].\end{aligned}$$

Proof. Following the update rule in `Pullback-STORM`, we could have the update rule of $\boldsymbol{\epsilon}$ described as

$$\begin{aligned}\boldsymbol{\epsilon}_{t+1} &= \frac{1-a}{b} \sum_{i \le b} \left[\mathbf{d}_t - \nabla f(\mathbf{x}_t; \boldsymbol{\xi}_{t+1}^i)\right] + \frac{1}{b} \sum_{i \le b} \left[\nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1})\right] \\ &= \frac{a}{b} \sum_{i \le b} [\nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1})] + (1-a)(\mathbf{d}_t - \nabla F(\mathbf{x}_t)) \\ &\quad + \frac{1-a}{b} \sum_{i \le b} \left[\nabla F(\mathbf{x}_t) - \nabla f(\mathbf{x}_t; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1}) + \nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i)\right] \\ &= \frac{a}{b} \sum_{i \le b} [\nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1})] + (1-a)\boldsymbol{\epsilon}_t \\ &\quad + \frac{1-a}{b} \sum_{i \le b} \left[\nabla F(\mathbf{x}_t) - \nabla f(\mathbf{x}_t; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1}) + \nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i)\right],\end{aligned}$$

where the last equation is by definition $\boldsymbol{\epsilon}_t := \mathbf{d}_t - \nabla F(\mathbf{x}_t)$. Thus we have

$$\begin{aligned}&\frac{\boldsymbol{\epsilon}_{t+1}}{(1-a)^{t+1}} - \frac{\boldsymbol{\epsilon}_t}{(1-a)^t} \\ &= \frac{1}{(1-a)^{t+1}} \Big(\frac{a}{b} \sum_{i \le b} [\nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1})] \\ &\quad + \frac{1-a}{b} \sum_{i \le b} \left[\nabla F(\mathbf{x}_t) - \nabla f(\mathbf{x}_t; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1}) + \nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i)\right] \Big), \\ &= \frac{1}{(1-a)^{t+1}} \sum_{i \le b} \boldsymbol{\epsilon}_{t,i}.\end{aligned}$$

□

B.1 Proof of Lemma A.1

Proposition B.2. For two positive sequences $\{a_i\}_{i=1}^n$ and $\{b_i\}_{i=1}^n$. Suppose $C = \max_{i,j \in [n]} \{|a_i/a_j|\}$, $\bar{b} = \sum_{i=1}^n b_i/n$. Then we have,

$$\sum_{i=1}^n a_i b_i \le \max_i a_i \cdot n \cdot \bar{b} \le C \sum_{i=1}^n a_i \bar{b}.$$

Proof of Lemma A.1. By Proposition B.1 we have

$$\frac{\boldsymbol{\epsilon}_{t+1}}{(1-a)^{t+1}} - \frac{\boldsymbol{\epsilon}_t}{(1-a)^t} = \frac{1}{(1-a)^{t+1}} \sum_{i \le b} \boldsymbol{\epsilon}_{t,i}.$$

It is easy to verify that $\{\boldsymbol{\epsilon}_{t,i}\}$ forms a martingale difference sequence and

$$\begin{aligned}\|\boldsymbol{\epsilon}_{t,i}\|_2^2 &\le 2\bigg\|\frac{a}{b}[\nabla f(\mathbf{x}_{t+1};\boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1})]\bigg\|_2^2 \\ &\quad + 2\bigg\|\frac{1-a}{b}\big[\nabla F(\mathbf{x}_t) - \nabla f(\mathbf{x}_t;\boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1}) + \nabla f(\mathbf{x}_{t+1};\boldsymbol{\xi}_{t+1}^i)\big]\bigg\|_2^2 \\ &\le \frac{2a^2\sigma^2 + 8(1-a)^2L^2\|\mathbf{x}_{t+1} - \mathbf{x}_i\|_2^2}{b^2},\end{aligned}$$

where the first inequality holds due to triangle inequality, the second inequality holds due to Assumptions 3.1 and 3.2. Therefore, by Azuma-Hoeffding inequality (See Lemma D.1 for detail), with probability at least $1-\delta$, we have that for any $t > 0$,

$$\begin{aligned}\bigg\|\frac{\boldsymbol{\epsilon}_t}{(1-a)^t} - \frac{\boldsymbol{\epsilon}_0}{(1-a)^0}\bigg\|_2^2 &\le 4\log(4/\delta)\sum_{i=0}^{t-1} b\cdot\frac{2a^2\sigma^2 + 8(1-a)^2L^2\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2}{(1-a)^{2i+2}b^2} \\ &= 8\log(4/\delta)\sum_{i=0}^{t-1}\frac{a^2\sigma^2 + 4(1-a)^2L^2\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2}{(1-a)^{2i+2}b}.\end{aligned}$$

Therefore, we have

$$\begin{aligned}\|\boldsymbol{\epsilon}_t\|_2^2 &\le 2(1-a)^{2t}\bigg\|\frac{\boldsymbol{\epsilon}_t}{(1-a)^t} - \boldsymbol{\epsilon}_0\bigg\|_2^2 + 2(1-a)^{2t}\|\boldsymbol{\epsilon}_0\|_2^2 \\ &\le \log(4/\delta)\bigg[\frac{64L^2}{b}\sum_{i=0}^{t-1}(1-a)^{2t-2i}\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2 + \frac{16a\sigma^2}{b}\bigg] + 2(1-a)^{2t}\|\boldsymbol{\epsilon}_0\|_2^2. \quad \text{(B.1)}\end{aligned}$$

By Azuma-Hoeffding Inequality, we have with probability $1-\delta$,

$$\|\boldsymbol{\epsilon}_0\|_2^2 = \bigg\|\frac{1}{B}\sum_{1\le i\le B}\Big[\nabla f(\mathbf{x}_0;\boldsymbol{\xi}_0^i) - \nabla F(\mathbf{x}_0)\Big]\bigg\|_2^2 \le \frac{4\log(4/\delta)\sigma^2}{B}.$$

Therefore, with probability $1-2\delta$, we have

$$\begin{aligned}\|\boldsymbol{\epsilon}_t\|_2^2 &\le \log(4/\delta)\bigg[\frac{64L^2}{b}\sum_{i=0}^{t-1}(1-a)^{2t-2i-2}\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2 + \frac{16a\sigma^2}{b} + \frac{32(1-a)^{2t}\sigma^2}{B}\bigg] \\ &= \frac{64L^2\log(4/\delta)}{b}\underbrace{\sum_{i=0}^{t-1}(1-a)^{2t-2i-2}\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2}_{I} + \frac{16a\sigma^2\log(4/\delta)}{b} \quad \text{(B.2)} \\ &\quad + \frac{32(1-a)^{2t}\log(4/\delta)\sigma^2}{B}. \quad \text{(B.3)}\end{aligned}$$

We now bound I. Denote $S_1 = \{i \in [t-1] | \exists j, t_j \le i < m_j\}$, $S_2 = \{i \in [t-1] | \exists j, i = m_j\}$, $S_3 = \{i \in [t-1] | \exists j, m_j < i < t_{j+1}\}$, We can divide I into three part,

$$\begin{aligned}I &= \underbrace{\sum_{i\in S_1}(1-a)^{2t-2i-2}\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2}_{I_1} + \underbrace{\sum_{i\in S_2}(1-a)^{2t-2i-2}\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2}_{I_2} \\ &\quad + \underbrace{\sum_{i\in S_3}^{t-1}(1-a)^{2t-2i-2}\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2}_{I_3}. \quad \text{(B.4)}\end{aligned}$$

Because $\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2 = \eta_t\|\mathbf{d}_i\|_2 = \eta$, we can bound I_1 as follows,

$$I_1 = \eta^2\sum_{i\in S_1}(1-a)^{2t-2i-2} \le \eta^2\sum_{i=0}^{\infty}(1-a)^i = \frac{\eta^2}{a}. \quad \text{(B.5)}$$

Because the perturbation radius is r, we can bound I_2 as follows,

$$I_2 = \sum_{i\in S_2} (1-a)^{2t-2i-2}\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2 \le r^2 \sum_{i\in S_2}(1-a)^{2t-2i-2} \le \frac{r^2}{a}. \tag{B.6}$$

To bound I_3, we have

$$\begin{aligned}
I_3 &= \sum_{i\in S_3}^{t-1} (1-a)^{2t-2i-2}\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2 \\
&= \sum_{s=1}^{S} \sum_{i=m_s+1}^{\min\{t-1, t_{s+1}-1\}} (1-a)^{2t-2i-2}\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2 \\
&\le \sum_{s=1}^{S} (1-a)^{-2\ell_{\text{thres}}} \sum_{i=m_s+1}^{\min\{t-1, t_{s+1}-1\}} (1-a)^{2t-2i-2}\overline{D} \\
&= (1-a)^{-2\ell_{\text{thres}}} \sum_{i\in S_3}^{t-1} (1-a)^{2t-2i-2}\overline{D} \\
&\le \frac{\overline{D}(1-a)^{-2\ell_{\text{thres}}}}{a},
\end{aligned} \tag{B.7}$$

where S satisfies $m_S < t-1 < t_{S+1}$. The first inequality holds due to Proposition B.2 with the fact that the average of $\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2$ is bounded by $\bar{D}$, according to the `Pullback` scheme, and $t_{s+1} - m_s < \ell_{\text{thres}}$, the last one holds trivially. Substituting (B.5), (B.6), (B.7) into (B.4), we have

$$I \le \frac{\eta^2 + r^2 + (1-a)^{2\ell_{\text{thres}}}\overline{D}}{a}.$$

Therefore (B.3) can further bounded by

$$\|\boldsymbol{\epsilon}_t\|_2^2 \le \frac{64L^2\log(4/\delta)}{b}\frac{\eta^2 + r^2 + (1-a)^{2\ell_{\text{thres}}}\overline{D}}{a} + \frac{16a\sigma^2\log(4/\delta)}{b} + \frac{32(1-a)^{2t}\log(4/\delta)\sigma^2}{B}. \tag{B.8}$$

By the selection of $\eta \le \sigma/(2bL)$, $r \le \sigma/(2bL)$ and $\overline{D} \le \sigma^2/(4b^2L^2)$, $a = 56^2\log(4/\delta)/b$, $B = b^2$,$a \le 1/4\ell_{\text{thres}}$, it's easy to verify that

$$\frac{64L^2\log(4/\delta)}{b}\frac{\eta^2 + r^2 + 2\overline{D}}{a} \le \frac{\sigma^2}{b^2} \tag{B.9}$$

$$(1-a)^{2\ell_{\text{thres}}} \ge 1 - 2a\ell_{\text{thres}} \ge \frac{1}{2} \tag{B.10}$$

$$\frac{16a\sigma^2\log(4/\delta)}{b} \le \frac{224^2\sigma^2\log(4/\delta)^2}{b^2} \tag{B.11}$$

$$\frac{32\log(4/\delta)\sigma^2}{B} \le \frac{32\log(4/\delta)\sigma^2}{b^2}. \tag{B.12}$$

Plugging (B.9) to (B.12) into (B.8) gives,

$$\|\boldsymbol{\epsilon}_t\|_2 \le \frac{2^{10}\log(4/\delta)\sigma}{b}.$$

□

B.2 Proof of Lemma A.3

Lemma B.3 (Small stuck region)**.** Suppose $-\gamma = \lambda_{\min}(\nabla^2 F(\mathbf{x}_{m_s})) \le -\epsilon_H$. Set $\ell = 2\log(8\epsilon_H\rho^{-1}r_0^{-1})/(\eta_H\gamma)$, $\eta_H \le \min\{1/(10L\log(8\epsilon_H L\rho^{-1}r_0^{-1})), 1/(10L\log(\ell))\}$, $a \le \eta_H\gamma$, $r \le L\eta_H\epsilon_H/\rho$. Let $\{\mathbf{x}_t\}, \{\mathbf{x}'_t\}$ be two coupled sequences by running `Pullback-STORM` from $\mathbf{x}_{m_s+1}, \mathbf{x}'_{m_s+1}$ with $\mathbf{w}_{m_s+1} = \mathbf{x}_{m_s+1} - \mathbf{x}'_{m_s+1} = r_0\mathbf{e}_1$, where $\mathbf{x}_{m_s+1}, \mathbf{x}'_{m_s+1} \in \mathbb{B}_{\mathbf{x}_{m_s}}(r)$,

$r_0 = \delta r/\sqrt{d}$ and $\mathbf{e}_1$ denotes the smallest eigenvector direction of Hessian $\nabla^2 F(\mathbf{x}_{m_s})$. Moreover, let batch size $b \geq \max\{16\log(4/\delta)\eta_H^{-2}L^{-2}\gamma^{-2}, 56^2\log(4/\delta)a^{-1}\}$, then with probability $1-2\delta$ we have

$$\exists T \leq \ell, \max\{\|\mathbf{x}_T - \mathbf{x}_0\|_2, \|\mathbf{x}'_T - \mathbf{x}'_0\|_2\} \geq \frac{\eta_H \epsilon_H L}{\rho}.$$

Proof. See Appendix C.1. □

Proof of Lemma A.3. We assume $\lambda_{\min}(\nabla^2 F(\mathbf{x}_{m_s})) < -\epsilon_H$ and prove our statement by contradiction. Lemma B.3 shows that, in the random perturbation ball at least one of two points in the $\mathbf{e}_1$ direction will escape the saddle point if their distance is larger than $r_0 = \frac{\delta r}{\sqrt{d}}$. Thus, the probability of the starting point $\mathbf{x}_{m_s+1} \sim \mathbb{B}_{\mathbf{x}_{m_s}}(r)$ located in the stuck region uniformly is less than δ. Then with probability at least $1-2\delta$,

$$\exists m_s < t < m_s + \ell_{\text{thres}}, \|\mathbf{x}_t - \mathbf{x}_{m_s}\|_2 \geq \frac{L\eta_H\epsilon_H}{\rho}. \tag{B.13}$$

Suppose `Pullback-STORM` does not break, then for any $m_s < t < m_s + \ell_{\text{thres}}$,

$$\|\mathbf{x}_t - \mathbf{x}_{m_s}\|_2 \leq \sum_{i=m_s}^{t-1} \|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2 \leq \sqrt{(t-m_s)\sum_{i=m_s}^{t-1}\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2} \leq (t-m_s)\sqrt{\overline{D}},$$

where the first inequality is due to the triangle inequality and the second inequality is due to Cauchy-Schwarz inequality. Thus, by the selection of $\overline{D}$, we have

$$\|\mathbf{x}_t - \mathbf{x}_{m_s}\|_2 \leq (t-m_s)\sqrt{\overline{D}} \leq \ell_{\text{thres}}\sqrt{\overline{D}} < \frac{L\eta_H\epsilon_H}{\rho},$$

which contradicts (B.13). Therefore, we know that with probability at least $1-2\delta$, $\lambda_{\min}(\nabla^2 F(\mathbf{x}_{m_s})) \geq -\epsilon_H$. □

B.3 Proof of Lemma A.4

Proof of Lemma A.4. Suppose $m_s < i < t_{s+1}$. Then with probability at least $1-\delta$, then by Lemma D.2 we have

$$\begin{aligned} F(\mathbf{x}_{i+1}) &\leq F(\mathbf{x}_i) + \frac{\eta_i}{2}\|\boldsymbol{\epsilon}_i\|_2^2 - \left(\frac{1}{2\eta_i} - \frac{L}{2}\right)\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2 \\ &\leq F(\mathbf{x}_i) + \frac{\eta_H}{2}\frac{2^{20}\log(4/\delta)^2\sigma^2}{b^2} - \frac{1}{4\eta_H}\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2 \end{aligned} \tag{B.14}$$

where the the second inequality holds due to Lemma A.1 and the fact that for any $m_s < i < t_{s+1}$, $\eta_i \leq \eta_H \leq 1/(2L)$. Taking summation of (B.14) from $i = m_s+1$ to $t-1$, we have

$$F(\mathbf{x}_t) \leq F(\mathbf{x}_{m_s+1}) + 2^{19}\eta_H\log(4/\delta)^2(t-m_s-1)\frac{\sigma^2}{b^2} - \frac{1}{4\eta_H}\sum_{i=m_s+1}^{t-1}\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2. \tag{B.15}$$

Finally, we have

$$\begin{aligned} F(\mathbf{x}_{m_s+1}) - F(\mathbf{x}_{t_{s+1}}) &\geq \sum_{i=m_s+1}^{t_{s+1}-1}\frac{\|\mathbf{x}_{i+1} - \mathbf{x}_i\|_2^2}{4\eta_H} - 2^{19}\log(4/\delta)^2(t-m_s-1)\eta_H\frac{\sigma^2}{b^2} \\ &= (t_{s+1} - m_s - 1)\left(\frac{\overline{D}}{4\eta_H} - \frac{2^{19}\log(4/\delta)^2\eta_H\sigma^2}{b^2}\right) \\ &= (t_{s+1} - m_s - 1)\left(\frac{\sigma^2}{16\eta_H b^2 L^2} - \frac{2^{19}\log(4/\delta)^2\eta_H\sigma^2}{b^2}\right) \\ &\geq (t_{s+1} - m_s - 1)\frac{4\log(4/\delta)^2\eta_H\sigma^2}{b^2}, \end{aligned} \tag{B.16}$$

where the last inequality is by the selection of $\eta_H \le 1/\big(2^{12}L\log(4/\delta)\big)$. For $i = m_s$, by Lemma D.2 we have

$$\begin{aligned} F(\mathbf{x}_{m_s+1}) &\le F(\mathbf{x}_t) + (2\|\mathbf{d}_t\|_2 + 2\|\boldsymbol{\epsilon}_t\|_2 + Lr/2)r \\ &\le F(\mathbf{x}_{m_s}) + (4\epsilon + Lr/2)r \\ &\le F(\mathbf{x}_{m_s}) + \frac{2\log(4/\delta)^2\eta_H\sigma^2}{b^2}, \end{aligned} \tag{B.17}$$

where the last inequality is by the selection, $r \le \min\big\{\log(4/\delta)^2\eta_H\sigma^2/(4b^2\epsilon), \sqrt{2\log(4/\delta)^2\eta_H\sigma^2/(b^2L)}\big\}$.
Combining (B.16) and (B.17) we have that

$$\begin{aligned} F(\mathbf{x}_{m_s}) - F(\mathbf{x}_{t_{s+1}}) &= F(\mathbf{x}_{m_s}) - F(\mathbf{x}_{m_s+1}) + F(\mathbf{x}_{m_s+1}) - F(\mathbf{x}_{t_{s+1}}) \\ &\ge (t_{s+1} - m_s - 1)\frac{4\log(4/\delta)^2\eta_H\sigma^2}{b^2} - \frac{2\log(4/\delta)^2\eta_H\sigma^2}{b^2} \\ &\ge (t_{s+1} - m_s)\frac{\log(4/\delta)^2\eta_H\sigma^2}{b^2}, \end{aligned}$$

where we use the fact that $t_{s+1} - m_s \ge 2$. □

C Proof of Lemmas in Section B

C.1 Proof of Lemma B.3

Define $\mathbf{w}_t := \mathbf{x}_t - \mathbf{x}'_t$ as the distance between the two coupled sequences. By the construction, we have that $\mathbf{w}_0 = r_0\mathbf{e}_1$, where $\mathbf{e}_1$ is the smallest eigenvector direction of Hessian $\mathcal{H} := \nabla^2 F(\mathbf{x}_{m_s})$.

$$\begin{aligned} \mathbf{w}_t &= \mathbf{w}_{t-1} - \eta(\mathbf{d}_{t-1} - \mathbf{d}'_{t-1}) \\ &= \mathbf{w}_{t-1} - \eta(\nabla F(\mathbf{x}_{t-1}) - \nabla F(\mathbf{x}'_{t-1}) + \mathbf{d}_{t-1} - F(\mathbf{x}_{t-1}) - \mathbf{d}'_{t-1} + \nabla F(\mathbf{x}'_{t-1})) \\ &= \mathbf{w}_{t-1} - \eta\bigg[(\mathbf{x}_{t-1} - \mathbf{x}'_{t-1})\int_0^1 \nabla^2 F(\mathbf{x}'_{t-1} + \theta(\mathbf{x}_{t-1} - \mathbf{x}'_{t-1}))d\theta \\ &\qquad + \mathbf{d}_{t-1} - F(\mathbf{x}_{t-1}) - \mathbf{d}'_{t-1} + F(\mathbf{x}'_{t-1})\bigg] \\ &= (1 - \eta\mathcal{H})\mathbf{w}_{t-1} - \eta(\Delta_{t-1}\mathbf{w}_{t-1} + \mathbf{y}_{t-1}), \end{aligned}$$

where

$$\begin{aligned} \Delta_{t-1} &:= \int_0^1 (\nabla^2 F(\mathbf{x}'_{t-1} + \theta(\mathbf{x}_{t-1} - \mathbf{x}'_{t-1})) - \mathcal{H})d\theta, \\ \mathbf{y}_{t-1} &:= \mathbf{d}_{t-1} - \nabla F(\mathbf{x}_{t-1}) - \mathbf{d}'_{t-1} + \nabla F(\mathbf{x}'_{t-1}) = \boldsymbol{\epsilon}_{t-1} - \boldsymbol{\epsilon}'_{t-1}. \end{aligned}$$

Recursively applying the above equation, we get

$$\mathbf{w}_t = (1 - \eta\mathcal{H})^{t-m_s-1}\mathbf{w}_{m_s+1} - \eta\sum_{\tau=m_s+1}^{t-1}(1 - \eta\mathcal{H})^{t-1-\tau}(\Delta_\tau\mathbf{w}_\tau + \mathbf{y}_\tau). \tag{C.1}$$

We want to show that the first term of (C.1) dominates the second term. Next Lemma is essential for the proof of Lemma B.3, which bounds the norm of $\mathbf{y}_t$.

Lemma C.1. Under Assumption 3.1, we have following inequality holds,

$$\begin{aligned} \|\mathbf{y}_t\|_2 &\le 2\sqrt{\log(4/\delta)}b^{-1/2}a^{-1/2}\Big(2L\max_{m_s<\tau<t}\|\mathbf{w}_{\tau+1} - \mathbf{w}_\tau\|_2 \\ &\qquad + \max_{m_s<\tau\le t}(2aL + 4\rho D_\tau)\cdot\max_{m_s<\tau\le t}\|\mathbf{w}_\tau\|_2\Big) + 4\sqrt{\log(4/\delta)}b^{-1/2}Lr_0, \end{aligned} \tag{C.2}$$

where $D_\tau = \max\{\|\mathbf{x}_\tau - \mathbf{x}_{m_s}\|_2, \|\mathbf{x}'_\tau - \mathbf{x}_{m_s}\|_2\}$.

Proof of Lemma C.1. By Proposition B.1, we have that

$$\frac{\mathbf{y}_{t+1}}{(1-a)^{t+1}} - \frac{\mathbf{y}_t}{(1-a)^t} = \frac{\boldsymbol{\epsilon}_{t+1}}{(1-a)^{t+1}} - \frac{\boldsymbol{\epsilon}_t}{(1-a)^t} - \frac{\boldsymbol{\epsilon}'_{t+1}}{(1-a)^{t+1}} + \frac{\boldsymbol{\epsilon}'_t}{(1-a)^t}$$

$$= \frac{1}{(1-a)^{t+1}} \sum_{i \le b} [\boldsymbol{\epsilon}_{t,i} - \boldsymbol{\epsilon}'_{t,i}],$$

where $\boldsymbol{\epsilon}_{t,i}$ is the same as that in Proposition B.1:

$$\begin{aligned} \boldsymbol{\epsilon}_{t,i} &= \frac{a}{b}[\nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1})] \\ &\quad + \frac{1-a}{b}\big[\nabla F(\mathbf{x}_t) - \nabla f(\mathbf{x}_t; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1}) + \nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i)\big] \\ &= \frac{1}{b}[\nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1})] + \frac{1-a}{b}\big[\nabla F(\mathbf{x}_t) - \nabla f(\mathbf{x}_t; \boldsymbol{\xi}_{t+1}^i)\big], \end{aligned} \tag{C.3}$$

where we rewrite $\boldsymbol{\epsilon}_{t,i}$ as (C.3) because now we want bound the $\boldsymbol{\epsilon}_t - \boldsymbol{\epsilon}'_t$ by the distance between two sequence. $\boldsymbol{\epsilon}'_{t,i}$ is defined similarly as follows

$$\boldsymbol{\epsilon}'_{t,i} = \frac{1}{b}[\nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1})] + \frac{1-a}{b}\big[\nabla F(\mathbf{x}_t) - \nabla f(\mathbf{x}_t; \boldsymbol{\xi}_{t+1}^i)\big].$$

It is easy to verify that $\{\boldsymbol{\epsilon}_{t,i} - \boldsymbol{\epsilon}'_{t,i}\}$ forms a martingale difference sequence. We now bound $\|\boldsymbol{\epsilon}_{t,i} - \boldsymbol{\epsilon}_{t,i'}\|_2^2$. Denote $\mathcal{H}_{t+1,i} = \nabla^2 f(\mathbf{x}_{m_s}; \boldsymbol{\xi}_{t+1}^i)$, then we introduce two terms

$$\begin{aligned} \Delta_{t+1,i} &:= \int_0^1 \big(\nabla^2 f(\mathbf{x}'_{t+1} + \theta(\mathbf{x}_{t+1} - \mathbf{x}'_{t+1}); \boldsymbol{\xi}_{t+1}^i) - \mathcal{H}_{t+1,i}\big) d\theta \\ \widehat{\Delta}_{t+1,i} &:= \int_0^1 \big(\nabla^2 f(\mathbf{x}'_t + \theta(\mathbf{x}_t - \mathbf{x}'_t); \boldsymbol{\xi}_{t+1}^i) - \mathcal{H}_{t+1,i}\big) d\theta, \end{aligned}$$

By Assumption 3.1, we have $\|\Delta_{t+1,i}\|_2 \le \rho \max_{\theta \in [0,1]} \|\mathbf{x}'_{t+1} + \theta(\mathbf{x}_{t+1} - \mathbf{x}'_{t+1}) - \mathbf{x}_{m_s+1}\|_2 \le \rho D_{t+1}$, similarly we have $\|\widehat{\Delta}_{t+1,i}\|_2 \le \rho D_t$ and $\Delta_{t+1} \le \rho D_{t+1}$.

Now we bound $\boldsymbol{\epsilon}_{t,i} - \boldsymbol{\epsilon}'_{t,i}$,

$$\begin{aligned} b(\boldsymbol{\epsilon}_{t,i} - \boldsymbol{\epsilon}'_{t,i}) &= \Big([\nabla f(\mathbf{x}_{t+1}; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}_{t+1})] + (1-a)\big[\nabla F(\mathbf{x}_t) - \nabla f(\mathbf{x}_t; \boldsymbol{\xi}_{t+1}^i)\big]\Big) \\ &\quad - \Big([\nabla f(\mathbf{x}'_{t+1}; \boldsymbol{\xi}_{t+1}^i) - \nabla F(\mathbf{x}'_{t+1})] - (1-a)\big[\nabla F(\mathbf{x}'_t) - \nabla f(\mathbf{x}'_t; \boldsymbol{\xi}_{t+1}^i)\big]\Big) \\ &= \big(\mathcal{H}_{t+1,i}\mathbf{w}_{t+1} + \Delta_{t+1,i}\mathbf{w}_{t+1} - \mathcal{H}\mathbf{w}_{t+1} - \Delta_{t+1}\mathbf{w}_{t+1} + (1-a)\mathcal{H}\mathbf{w}_t \\ &\quad + (1-a)\Delta_t\mathbf{w}_t - (1-a)\mathcal{H}_{t+1,i}\mathbf{w}_t - (1-a)\widehat{\Delta}_{t+1,i}\mathbf{w}_t\big) \\ &= \big(\mathcal{H}_{t+1,i} - \mathcal{H}\big)\big(\mathbf{w}_{t+1} - (1-a)\mathbf{w}_t\big) + \big(\Delta_{t+1,i} - \Delta_{t+1}\big)\mathbf{w}_{t+1} \\ &\quad + (1-a)\big(\Delta_t - \widehat{\Delta}_{t+1,i}\big)\mathbf{w}_t. \end{aligned} \tag{C.4}$$

This implies the LHS of (C.4) has the following bound.

$$\begin{aligned} \|b(\boldsymbol{\epsilon}_{t,i} - \boldsymbol{\epsilon}'_{t,i})\|_2 &\le 2L\|\mathbf{w}_{t+1} - (1-a)\mathbf{w}_t\|_2 + 2\rho D_{t+1}^x\|\mathbf{w}_{t+1}\|_2 + 2\rho D_t^x\|\mathbf{w}_t\|_2 \\ &\le 2L\|\mathbf{w}_{t+1} - \mathbf{w}_t\|_2 + 2\rho D_{t+1}^x\|\mathbf{w}_{t+1}\|_2 + (2aL + 2\rho D_t^x)\|\mathbf{w}_t\|_2 \\ &\le \underbrace{2L \max_{m_s < \tau < t}\|\mathbf{w}_{\tau+1} - \mathbf{w}_\tau\|_2 + \max_{m_s < \tau \le t}(2aL + 4\rho D_\tau) \cdot \max_{m_s < \tau \le t}\|\mathbf{w}_\tau\|_2}_{M} \end{aligned}$$

where the first inequality is by the gradient Lipschitz Assumption and Hessian Lipschitz Assumption 3.1, the second inequality is by triangle inequality. Therefore we have

$$\|\boldsymbol{\epsilon}_{t,i} - \boldsymbol{\epsilon}'_{t,i}\|_2^2 \le \frac{M^2}{b^2}$$

Furthermore, by Azuma Hoeffding inequality(See Lemma D.1 for detail), with probability at least $1-\delta$, we have that for any $t > 0$,

$$\left\|\frac{\mathbf{y}_t}{(1-a)^t} - \frac{\mathbf{y}_{m_s+1}}{(1-a)^{m_s+1}}\right\|_2^2 = \left\|\sum_{\tau=m_s+1}^{t-1}\left(\frac{\mathbf{y}_{\tau+1}}{(1-a)^{\tau+1}} - \frac{\mathbf{y}_\tau}{(1-a)^\tau}\right)\right\|_2^2$$

$$= \left\| \sum_{\tau=m_s+1}^{t-1} \left(\frac{1}{(1-a)^{\tau+1}} \sum_{i\le b} [\boldsymbol{\epsilon}_{\tau,i} - \boldsymbol{\epsilon}'_{\tau,i}] \right) \right\|_2^2$$
$$\le 4\log(4/\delta) \left(\sum_{i=m_s+1}^{t-1} b \cdot \frac{M^2}{(1-a)^{2\tau+2} b^2} \right).$$

Multiply $(1-a)^{2t}$ on both side, we get

$$\|\mathbf{y}_t - (1-a)^{t-m_s-1}\mathbf{y}_{m_s+1}\|_2^2 \le 4b^{-1}\log(4/\delta) \sum_{\tau=m_s+1}^{t-1} (1-a)^{2t-2\tau-2} M^2$$
$$\le 4\log(4/\delta) b^{-1} a^{-1} M^2,$$

where the last inequality is by $\sum_{i=0}^{t-1}(1-a)^{2t-2i-2} \le a^{-1}$. Furthermore, by triangle inequality we have

$$\|\mathbf{y}_t\|_2 \le 2\sqrt{log(4/\delta)} b^{-1/2} a^{-1/2} M + (1-a)^{t-m_s-1}\|\mathbf{y}_{m_s+1}\|_2. \tag{C.5}$$

$\|\nabla f(\mathbf{x}_{m_s+1}; \boldsymbol{\xi}^i_{m_s+1}) - \nabla F(\mathbf{x}'_{m_s+1}) - \nabla f(\mathbf{x}'_{m_s+1}; \boldsymbol{\xi}^i_{m_s+1}) + \nabla F(\mathbf{x}'_{m_s+1})\|_2 \le 2Lr_0$ due to Assumption 3.1. Then by Azuma Inequality(See Lemma D.1), we have with probability at least $1-\delta$,

$$\|\mathbf{y}_{m_s+1}\|_2^2 = \|\mathbf{d}_{m_s+1} - \nabla F(\mathbf{x}_{m_s+1}) - \mathbf{d}'_{m_s+1} + \nabla F(\mathbf{x}'_{m_s+1})\|_2^2$$
$$= \left\| \frac{1}{b} \sum_{i\le b} [\nabla f(\mathbf{x}_{m_s+1}; \boldsymbol{\xi}^i_{m_s+1}) - \nabla F(\mathbf{x}'_{m_s+1}) - \nabla f(\mathbf{x}'_{m_s+1}; \boldsymbol{\xi}^i_{m_s+1}) + \nabla F(\mathbf{x}'_{m_s+1})] \right\|_2^2$$
$$\le \frac{4\log(4/\delta) 4L^2 r_0^2}{b}. \tag{C.6}$$

Plugging (C.6) into (C.5) gives

$$\|\mathbf{y}_t\|_2 \le 2\sqrt{\log(4/\delta)} b^{-1/2} a^{-1/2} \Big(2L \max_{m_s<\tau<t} \|\mathbf{w}_{\tau+1} - \mathbf{w}_\tau\|_2$$
$$+ \max_{m_s<\tau\le t} (2aL + 4\rho D_\tau) \cdot \max_{m_s<\tau\le t} \|\mathbf{w}_\tau\|_2 \Big) + 4\sqrt{\log(4/\delta)} b^{-1/2} L r_0.$$

□

Now we can give a proof of Lemma B.3.

Proof of Lemma B.3. We proof it by induction that

1. $\frac{1}{2}(1+\eta_H\gamma)^{t-m_s-1} r_0 \le \|\mathbf{w}_t\|_2 \le \frac{3}{2}(1+\eta_H\gamma)^{t-m_s-1} r_0$.
2. $\|y_t\|_2 \le 2\eta_H\gamma L(1+\eta_H\gamma)^{t-m_s-1} r_0$.

First for $t = m_s + 1$, we have $\|\mathbf{w}_{m_s+1}\|_2 = r_0$, $\|y_{m_s+1}\|_2 \le \sqrt{16b^{-1}\log(4/\delta)L^2 r_0^2} \le 2\eta_H\gamma L r_0$(See (C.6)), where $b \ge 2\eta_H^{-2}\gamma^{-2}\sqrt{\log(4/\delta)}$. Assume they hold for all $m_s < \tau < t$, we now prove they hold for t. We bound $\mathbf{w}_t$ first, we only need to show that second term of (C.1) is bounded by $\frac{1}{2}(1+\eta_H\gamma)^t r_0$.

$$\left\| \eta_H \sum_{\tau=m_s+1}^{t-1} (1-\eta_H\mathcal{H})^{t-1-\tau} (\Delta_\tau \mathbf{w}_\tau + \mathbf{y}_\tau) \right\|_2$$
$$\le \eta_H \sum_{\tau=m_s+1}^{t-1} (1+\eta_H\gamma)^{t-1-\tau} (\|\Delta_\tau\|_2 \|\mathbf{w}_\tau\|_2 + \|\mathbf{y}_\tau\|_2)$$

$$
\begin{aligned}
&\le \eta_H \sum_{\tau=m_s+1}^{t-1} (1+\eta_H\gamma)^{t-m_s-2} r_0 (\frac{3}{2}\|\Delta_\tau\|_2 + 2\eta_H\gamma L) \\
&\le \eta_H \sum_{\tau=m_s+1}^{t-1} (1+\eta_H\gamma)^{t-m_s-2} r_0 (3\eta_H\epsilon_H L + 2\eta_H\gamma L) \\
&= \eta_H \ell (1+\eta_H\gamma)^{t-m_s-2} r_0 \cdot 5\eta_H\gamma L \\
&\le 10\log(8\epsilon_H\rho^{-1}r_0^{-1})\eta_H L(1+\eta_H\gamma)^{t-m_s-2} r_0 \\
&\le \frac{1}{2}(1+\eta_H\gamma)^{t-m_s-1} r_0,
\end{aligned}
$$

where the first inequality is by the eigenvalue assumption over $\mathcal{H}$, the second inequality is by the Induction hypothesis, the third inequality is by $\|\Delta_\tau\|_2 \le \rho D_\tau = \rho \max\{\|\mathbf{x}_\tau - \mathbf{x}_{m_s}\|_2, \|\mathbf{x}'_\tau - \mathbf{x}_{m_s}\|_2\} \le \eta_H\epsilon_H L + r\rho \le 2\eta_H\epsilon_H L$, the fourth inequality is by the choice of $t - m_s - 1 \le \ell \le 2\log(8\epsilon_H\rho^{-1}r_0^{-1})/(\eta_H\gamma)$, the last inequality is by the choice of $\eta_H \le 1/(10\log(8\epsilon_H\rho^{-1}r_0^{-1})L)$.
Now we bound $\|\mathbf{y}_t\|_2$ by (C.2). We first get the bound for $L\|\mathbf{w}_{i+1} - \mathbf{w}_i\|_2$ as follows,

$$
\begin{aligned}
&L\|\mathbf{w}_{t+1} - \mathbf{w}_t\|_2 \\
&= L\bigg\| -\eta_H\mathcal{H}(I-\eta_H\mathcal{H})^{t-m_s-2}\mathbf{w}_0 - \eta_H \sum_{\tau=m_s+1}^{t-2} \eta_H\mathcal{H}(I-\eta_H\mathcal{H})^{t-2-\tau}(\Delta_\tau\mathbf{w}_\tau + \mathbf{y}_\tau) \\
&\qquad + \eta_H(\Delta_{t-1}\mathbf{w}_{t-1} + \mathbf{y}_{t-1})\bigg\|_2 \\
&\overset{(i)}{\le} L\eta_H\gamma(1+\eta_H\gamma)^{t-m_s-2} r_0 + L\eta_H \bigg\| \sum_{\tau=m_s+1}^{t-2} \eta_H\mathcal{H}(I-\eta_H\mathcal{H})^{t-2-\tau}(\Delta_\tau\mathbf{w}_\tau + \mathbf{y}_\tau)\bigg\|_2 \\
&\qquad + L\eta_H\bigg\|\Delta_{t-1}\mathbf{w}_{t-1} + \mathbf{y}_{t-1}\bigg\|_2 \\
&\overset{(ii)}{\le} L\eta_H\gamma(1+\eta_H\gamma)^{t-m_s-2} r_0 \\
&\qquad + L\eta_H\bigg[\bigg\|\sum_{\tau=m_s+1}^{t-2} \eta_H\mathcal{H}(I-\eta_H\mathcal{H})^{t-2-\tau}\bigg\|_2 + 1\bigg] \max_{0\le\tau\le t-1}\bigg\|\Delta_\tau\mathbf{w}_\tau + \mathbf{y}_\tau\bigg\|_2 \\
&\overset{(iii)}{\le} L\eta_H\gamma(1+\eta_H\gamma)^{t-m_s-2} r_0 + L\eta_H\bigg[\sum_{\tau=m_s+1}^{t-2} \frac{1}{t-1-\tau} + 1\bigg] \max_{0\le\tau\le t-1}\bigg\|\Delta_\tau\mathbf{w}_\tau + \mathbf{y}_\tau\bigg\|_2 \\
&\overset{(iv)}{\le} L\eta_H\gamma(1+\eta_H\gamma)^{t-m_s-2} r_0 + L\eta_H[\log(t-m_s-1)+1]\cdot[5\eta_H\gamma L(1+\eta_H\gamma)^{t-m_s-2} r_0] \\
&\overset{(v)}{\le} 6L\eta_H\gamma(1+\eta_H\gamma)^{t-m_s-2} r_0 + 5\log(t-m_s-1)\gamma\eta_H^2 L^2(1+\eta_H\gamma)^{t-m_s-2} r_0,
\end{aligned}
\tag{C.7}
$$

where (i) is by triangle inequality, (ii) is by the definition of max, (iii) is by $\|\eta_H\mathcal{H}(I - \eta_H\mathcal{H})^{t-2-\tau}\|_2 \le \frac{1}{t-1-\tau}$, (iv) is due to $\|\Delta_\tau\|_2 \le \rho D_\tau \le \rho(\eta_H\gamma L/\rho + r) \le 2\gamma\eta_H L$, $\|\mathbf{w}_\tau\|_2 \le 3(1+\eta_H\gamma)^{\tau-m_s-1}r_0/2$ and $\|\mathbf{y}_\tau\|_2 \le 2\eta_H\gamma L(1+\eta_H\gamma)^{\tau-m_s-1}r_0$, (v) is due to $\eta_H \le 1/L$.

We next get the bound of $\max_{m_s<\tau\le t}(2aL + 4\rho D_\tau)\cdot\max_{m_s<\tau\le t}\|\mathbf{w}_\tau\|_2$ as follows

$$
\begin{aligned}
\max_{m_s<\tau\le t}(2aL + 4\rho D_\tau)\cdot\max_{m_s<\tau\le t}\|\mathbf{w}_\tau\|_2 &\le (2aL + 8\gamma\eta_H L)\frac{3(1+\eta_H\gamma)^{t-m_s-1}}{2} r_0 \\
&\le 15\gamma\eta_H L(1+\eta_H\gamma)^{t-m_s-1} r_0.
\end{aligned}
\tag{C.8}
$$

where the first inequality is by $\rho D_t \le \rho(\gamma\eta_H L/\rho + r) \le 2\gamma\eta_H L$ and the induction hypothesis, last inequality is by $a \le \gamma\eta_H$.

Plugging (C.7) and (C.8) into (C.2) gives,

$$
\|\mathbf{y}_t\|_2 \le 2\sqrt{\log(4/\delta)}b^{-1/2}a^{-1/2}\Big(2L\max_{m_s<\tau<t}\|\mathbf{w}_{\tau+1} - \mathbf{w}_\tau\|_2
$$

$$
\begin{aligned}
&+ \max_{m_s<\tau\le t}(2aL+4\rho D_\tau)\cdot \max_{m_s<\tau\le t}\|\mathbf{w}_\tau\|_2\Big) + 4\sqrt{\log(4/\delta)}b^{-1/2}Lr_0\\
&\le 2\sqrt{\log(4/\delta)}b^{-1/2}a^{-1/2}\Big(10\log(\ell)\gamma\eta_H^2L^2(1+\eta_H\gamma)^{t-m_s-1}r_0\\
&\quad + 27\gamma\eta_H L(1+\eta_H\gamma)^{t-m_s-1}r_0\Big) + 4\sqrt{\log(4/\delta)}b^{-1/2}Lr_0\\
&\le \underbrace{56\sqrt{\log(4/\delta)}b^{-1/2}a^{-1/2}\eta_H L\gamma(1+\eta_H\gamma)^{t-m_s-1}r_0}_{I_1}\\
&\quad + \underbrace{4\sqrt{\log(4/\delta)}b^{-1/2}(1+\eta_H\gamma)^{t-m_s-1}r_0}_{I_2}
\end{aligned}
$$

where the last inequality is by $\eta_H \le 1/(10L\log\ell)$. Now we bound I_1 and I_2 respectively.

$$
\begin{aligned}
I_1 &= 56\sqrt{\log(4/\delta)}b^{-1/2}a^{-1/2}\eta_H L\gamma(1+\eta_H\gamma)^{t-m_s-1}r_0\\
&= \eta_H\gamma L(1+\eta_H\gamma)^{t-m_s-1}r_0,
\end{aligned}
$$

where the inequality is applying $b \ge 56^2\log(4/\delta)a^{-1}$. Now we bound I_2 by applying $b \ge 16\log(4/\delta)\eta_H^{-2}L^{-2}\gamma^{-2}$,

$$I_2 \le \eta_H\gamma L(1+\eta_H\gamma)^{t-m_s-1}r_0.$$

Then we obtain that

$$\|\mathbf{y}_t\|_2 \le 2\eta_H\gamma L(1+\eta_H\gamma)^{t-m_s-1}r_0,$$

which finishes the induction. So we have $\|\mathbf{w}_t\|_2 \ge \frac{1}{2}(1+\eta_H\gamma)^{t-m_s-1}r_0$. However, the triangle inequality give the bound

$$
\begin{aligned}
\|\mathbf{w}_t\|_2 &\le \|\mathbf{x}_t - \mathbf{x}_{m_{s+1}}\|_2 + \|\mathbf{x}_{m_{s+1}} - \mathbf{x}_{m_s}\|_2 + \|\mathbf{x}'_t - \mathbf{x}'_{m_s+1}\|_2 + \|\mathbf{x}'_{m_s+1} - \mathbf{x}'_{m_s}\|_2\\
&\le 2r + 2\frac{\epsilon_H\eta_H L}{\rho}\\
&\le 4\frac{\epsilon_H\eta_H L}{\rho},
\end{aligned}
$$

where the last inequality is due to $r \le \epsilon_H\eta_H L/\rho$. So we obtain that

$$t \le \frac{\log(8\epsilon_H\eta_H L\rho^{-1}r_0^{-1})}{\log(1+\eta_H\gamma)} < \frac{2\log(8\epsilon_H\rho^{-1}r_0^{-1})}{\eta_H\gamma}.$$

□

D Auxiliary Lemmas

We start by providing the Azuma–Hoeffding inequality under the vector settings.

Lemma D.1 (Theorem 3.5, Pinelis [24]). Let $\boldsymbol{\epsilon}_{1:k} \in \mathbb{R}^d$ be a vector-valued martingale difference sequence with respect to $\mathcal{F}_k$, i.e., for each $k \in [K]$, $\mathbb{E}[\boldsymbol{\epsilon}_k|\mathcal{F}_k] = 0$ and $\|\boldsymbol{\epsilon}_k\|_2 \le B_k$, then we have given $\delta \in (0,1)$, w.p. $1-\delta$,

$$\Big\|\sum_{i=1}^K \boldsymbol{\epsilon}_k\Big\|_2^2 \le 4\log(4/\delta)\sum_{i=1}^K B_k^2.$$

This lemma provides a dimension-free bound due to the fact that the Euclidean norm version of $\mathbb{R}^d$ is $(2,1)$ smooth, see also Kallenberg and Sztencel [15], Fang et al. [9]. Now, we are give a proof of Lemma 6.1.

We have the following lemma:

Lemma D.2. For any $t \ne m_s$, we have

$$F(\mathbf{x}_{t+1}) \le F(\mathbf{x}_t) - \frac{\eta_t}{2}\|\mathbf{d}_t\|_2^2 + \frac{\eta_t}{2}\|\boldsymbol{\epsilon}_t\|_2^2 + \frac{L}{2}\|\mathbf{x}_{t+1} - \mathbf{x}_t\|_2^2.$$

For $t = m_s$, we have $F(\mathbf{x}_{t+1}) \le F(\mathbf{x}_t) + (\|\mathbf{d}_t\|_2 + \|\boldsymbol{\epsilon}_t\|_2 + Lr/2)r$.

Proof of Lemma D.2. By Assumption 3.1, we have

$$F(\mathbf{x}_{t+1}) \le F(\mathbf{x}_t) + \langle \nabla F(\mathbf{x}_t), \mathbf{x}_{t+1} - \mathbf{x}_t \rangle + \frac{L}{2}\|\mathbf{x}_{t+1} - \mathbf{x}_t\|_2^2. \tag{D.1}$$

For the case $t \neq m_s$, the update rule is $\mathbf{x}_{t+1} = \mathbf{x}_t - \eta_t \mathbf{d}_t$, therefore

$$\begin{aligned} F(\mathbf{x}_{t+1}) &\le F(\mathbf{x}_t) - \eta_t \langle \nabla F(\mathbf{x}_t), \mathbf{d}_t \rangle + \frac{L}{2}\|\mathbf{x}_{t+1} - \mathbf{x}_t\|_2^2 \\ &= F(\mathbf{x}_t) - \eta_t \|\nabla F(\mathbf{x}_t)\|_2^2/2 - \eta_t \|\mathbf{d}_t\|_2^2/2 + \eta_t \|\boldsymbol{\epsilon}_t\|_2^2/2 + L\|\mathbf{x}_{t+1} - \mathbf{x}_t\|_2^2/2 \\ &\le F(\mathbf{x}_t) - \eta_t \|\mathbf{d}_t\|_2^2/2 + \eta_t \|\boldsymbol{\epsilon}_t\|_2^2/2 + \frac{L}{2}\|\mathbf{x}_{t+1} - \mathbf{x}_t\|_2^2, \end{aligned}$$

where the first inequality on the first line is due to Assumption 3.1 and the second inequality holds trivially. For the case $t = m_s$, since $\|\nabla F(\mathbf{x}_t)\|_2 \le \|\mathbf{d}_t\|_2 + \|\boldsymbol{\epsilon}_t\|_2$ we have

$$\begin{aligned} F(\mathbf{x}_{t+1}) &\le F(\mathbf{x}_t) + \langle \nabla F(\mathbf{x}_t), \mathbf{x}_{t+1} - \mathbf{x}_t \rangle + \frac{L}{2}\|\mathbf{x}_{t+1} - \mathbf{x}_t\|_2^2 \\ &\le F(\mathbf{x}_t) + (\|\mathbf{d}_t\|_2 + \|\boldsymbol{\epsilon}_t\|_2 + Lr/2)r. \end{aligned}$$

□

Lemma D.3 (Lemma 6, [17]). Suppose $-\gamma = \lambda_{\min}(\nabla^2 F(\mathbf{x}_{m_s})) \le -\epsilon_H$. Set $r \le L\eta_H\epsilon_H/(C\rho)$, $\ell_{\text{thres}} = 2\log(\eta_H\epsilon_H\sqrt{d}LC^{-1}\rho^{-1}\delta^{-1}r^{-1})/(\eta_H\epsilon_H) = \widetilde{O}(\eta_H^{-1}\epsilon_H^{-1})$, $\eta_H \le \min\{1/(16L\log(\eta_H\epsilon_H\sqrt{d}LC^{-1}\rho^{-1}\delta^{-1}r^{-1})), 1/(8CL\log\ell_{\text{thres}})\} = \widetilde{O}(L^{-1})$, $b = q = \sqrt{B} \ge 16\log(4/\delta)/(\eta_H^2\epsilon_H^2)$. Let $\{\mathbf{x}_t\}, \{\mathbf{x}'_t\}$ be two coupled sequences by running `Pullback-SPIDER` from $\mathbf{x}_{m_s+1}, \mathbf{x}'_{m_s+1}$ with $\mathbf{w}_{m_s+1} = \mathbf{x}_{m_s+1} - \mathbf{x}'_{m_s+1} = r_0\mathbf{e}_1$, where $\mathbf{x}_{m_s+1}, \mathbf{x}'_{m_s+1} \in \mathbb{B}_{\mathbf{x}_{m_s}}(r)$, $r_0 = \delta r/\sqrt{d}$ and $\mathbf{e}_1$ denotes the smallest eigenvector direction of Hessian $\nabla^2 F(\mathbf{x}_{m_s})$. Then with probability at least $1 - \delta$,

$$\max_{m_s < t < m_s + \ell_{\text{thres}}} \{\|\mathbf{x}_t - \mathbf{x}_{m_s}\|_2, \|\mathbf{x}_0 - \mathbf{x}_{m_s}\|_2\} \ge \frac{L\eta_H\epsilon_H}{C\rho}, \tag{D.2}$$

where $C = O(\log(d\ell_{\text{thres}}/\delta) = \widetilde{O}(1)$.