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A new algorithm driven from the view-point of the fluctuation-dissipation theorem in the theory of KM_2O -Langevin equations

YASUNORI OKABE

§1. Introduction

We have constructed in [4] a theory of KM_2O -Langevin equations for multi-dimensional weakly stationary processes with discrete time and found, from the point of view of the so-called fluctuation-dissipation theorem in irreversible statistical physics ([2]), a *fluctuation-dissipation theorem* which gives a relation between the fluctuant terms and the deterministic terms in the KM_2O -Langevin equations. *The fluctuation-dissipation theorem* had been already found as *Levinson-Whittle-Wiggins-Robinson algorithm* for the fitting of *AR-models* in the field of system, control and information ([3],[1],[10],[11]). By sublimating certain philosophical structure of the fluctuation-dissipation theorem into *the fluctuation-dissipation principle*, we have applied the theory of KM_2O -Langevin equations to data analysis to develop a *stationary analysis* and a *causal analysis* ([7],[6]). Furthermore, we have also used it to solve the non-linear prediction problem for one-dimensional strictly stationary processes with discrete time and developed a *prediction analysis* as the third project in data analysis ([5],[9],[8]).

Let $X = (X(n); n \in \mathbb{Z})$ be an $\mathbb{R}^d$ -valued weakly stationary process on a probability space $(\Omega, \mathcal{B}, P)$ with expectation vector zero and covariance matrix function R :

$$(1.1) \quad R(m-n) \equiv E(X(m)^t X(n)) \quad (m, n \in \mathbb{Z}),$$

where d is any fixed natural number.

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We define, for each $n \in \mathbb{N}$, a block Toeplitz matrix $S_n \in M(nd; \mathbb{R})$ by

$$(1.2) \quad S_n \equiv \begin{pmatrix} R(0) & R(1) & \dots & R(n-1) \\ R(-1) & R(0) & \dots & R(n-2) \\ \vdots & \vdots & \ddots & \vdots \\ R(-(n-1)) & R(-(n-2)) & \dots & R(0) \end{pmatrix}.$$

In this paper we shall treat the case where the following Toeplitz condition holds:

$$(1.3) \quad S_n \in GL(nd; \mathbb{R}) \quad \text{for any } n \in \mathbb{N}.$$

It then follows from the theory of KM_2O -Langevin equations that the time evolution *in the future* (resp. *in the past*) of the process $\mathbf{X}$ is governed by *the forward* (resp. *the backward*) KM_2O -Langevin equation (1.5₊) (resp. (1.5₋)) with (1.4):

$$(1.4) \quad X(0) = \nu_+(0) = \nu_-(0)$$

$$(1.5_+) \quad X(n) = - \sum_{k=1}^{n-1} \gamma_+(n, k) X(k) - \delta_+(n) X(0) + \nu_+(n) \quad (n \in \mathbb{N})$$

$$(1.5_-) \quad X(-n) = - \sum_{k=1}^{n-1} \gamma_-(n, k) X(-k) - \delta_-(n) X(0) + \nu_-(-n) \quad (n \in \mathbb{N}).$$

Here the random force $\nu_+ = (\nu_+(\ell); \ell \in \mathbb{N}^*)$ (resp. $\nu_- = (\nu_-(\ell); \ell \in -\mathbb{N}^*)$) is said to be *the forward* (resp. *the backward*) KM_2O -Langevin force associated with $\mathbf{X}$. We call the system $\{\gamma_+(n, k), \gamma_-(n, k), \delta_+(m), \delta_-(m), V_+(\ell), V_-(\ell); \ell \in \mathbb{N}^*, k, m, n \in \mathbb{N}, n > k\}$ whose elements belong to $M(d; \mathbb{R})$ *the KM_2O -Langevin data* associated with the covariance matrix function R of $\mathbf{X}$, where $V_{\pm}(\ell)$ are the covariance matrices of KM_2O -Langevin forces $\nu_{\pm}(\pm\ell)$ ($\ell \in \mathbb{N}^*$):

$$(1.6) \quad V_+(\ell) \equiv E(\nu_+(\ell)^t \nu_+(\ell)) \quad \text{and} \quad V_-(\ell) \equiv E(\nu_-(-\ell)^t \nu_-(-\ell)).$$

In particular, the subsystem $\{\delta_+(n), \delta_-(n); n \in \mathbb{N}\}$ is called *the partial autocorrelation coefficient* in the field of system, control and information.

The fluctuation-dissipation theorem stated in the first paragraph consists of the following relations (1.7_±)-(1.11):

Dissipation-Dissipation Theorem ([3],[1],[10],[11],[4]). For any $n, k \in \mathbb{N}$, $n > k$,

$$(1.7_{\pm}) \quad \gamma_{\pm}(n, k) = \gamma_{\pm}(n-1, k-1) + \delta_{\pm}(n) \gamma_{\mp}(n-1, n-k-1),$$

where

$$(1.8) \quad \gamma_{+}(n, 0) \equiv \delta_{+}(n) \quad \text{and} \quad \gamma_{-}(n, 0) \equiv \delta_{-}(n).$$

Fluctuation-Dissipation Theorem ([3],[1],[10],[11],[4]). For any $n \in \mathbb{N}$,

$$(1.9_{\pm}) \quad V_{\pm}(n) = (I - \delta_{\pm}(n) \delta_{\mp}(n)) V_{\pm}(n-1)$$

$$(1.10) \quad \delta_{-}(n) V_{+}(n-1) = V_{-}(n-1)^t \delta_{+}(n)$$

$$(1.11) \quad \delta_{-}(n) V_{+}(n) = V_{-}(n)^t \delta_{+}(n).$$

The review of the theory of KM_2O -Langevin equations reminds us that the relations (1.9 $_{\pm}$)-(1.11) result from the following *Burg's relation*:

Burg's relation ([3],[1],[10],[11],[4]). For any $n \in \mathbb{N}$,

$$(1.12) \quad \sum_{k=0}^{n-1} \gamma_{+}(n, k) R(k+1) = \sum_{k=0}^{n-1} R(k+1)^t \gamma_{-}(n, k).$$

As will be shown in §2, Burg's relation is really equivalent to the following relation:

$$(1.13) \quad E(\nu_{+}(n)^t \nu_{-}(-1)) = E(\nu_{+}(1)^t \nu_{-}(-n)) \quad (n \in \mathbb{N}^*).$$

From certain philosophical understanding of the fluctuation-dissipation theorem, relation (1.13) can be regarded as a special case of the so-called *fluctuation-fluctuation theorem*. The purpose of this paper is to obtain a general algorithm which holds among the mutual covariance matrix functions $I(m, n)$ of the forward KM_2O -Langevin force ν_{+} and the backward KM_2O -Langevin force ν_{-} :

$$(1.14) \quad I(m, n) \equiv E(\nu_{+}(m)^t \nu_{-}(-n)) \quad (m, n \in \mathbb{N}^*).$$

The main theorem is the following:

Fluctuation-Fluctuation Theorem.

- (i) $I(0, 0) = V_+(0)$
- (ii) $I(m, 0) = I(0, m) = 0 \quad (m \in \mathbb{N})$
- (iii) $I(m, 1) = I(1, m) = -\delta_+(m+1)V_-(m) \quad (m \in \mathbb{N})$
- (iv)
$$I(m, n) = I(m+1, n-1) + \left\{ \sum_{k=1}^{n-2} I(m+1, k) \delta_+(k+1) \right\}^t \delta_-(n) -$$

$$- \delta_+(m+1) \left\{ \sum_{k=1}^{m-1} \delta_-(k+1) I(k, n) \right\} \quad (m, n \geq 2).$$

This algorithm has been already announced in [5] and [9]. We shall show in the future that the *fluctuation-fluctuation theorem*, with the *dissipation-dissipation theorem* and the *fluctuation-dissipation theorem*, will give a characterization of the weak stationarity of the stochastic process X in terms of the KM_2O -Langevin forces ν_+ and ν_- .

§2. Proof of Fluctuation-Fluctuation Theorem

For any fixed natural number d , let $X = (X(n); n \in \mathbb{Z})$ be the same $\mathbb{R}^d$ -valued weakly stationary process as stated in §1.

We shall briefly remind of the definition of KM_2O -Langevin forces.

For any d -dimensional stochastic process $Y = ({}^t(Y_1(n), \dots, Y_d(n)); \ell \leq n \leq r)$ on the probability space $(\Omega, \mathcal{B}, P)$ $(-\infty \leq \ell < r \leq \infty)$, we define, for each $n_1, n_2, \ell \leq n_1 \leq n_2 \leq r$, the closed subspace $M_{n_1}^{n_2}(\mathbf{Y})$ of $L^2(\Omega, \mathcal{B}, P)$ by

$$(2.1) \quad M_{n_1}^{n_2}(\mathbf{Y}) \equiv \text{the closed linear hull of } \{Y_j(n); 1 \leq j \leq d, n_1 \leq n \leq n_2\}.$$

The forward (resp. the backward) KM_2O -Langevin force $\nu_+ = (\nu_+(n); n \in \mathbb{N}^*)$ (resp. $\nu_- = (\nu_-(\ell); \ell \in -\mathbb{N}^*)$) is an $\mathbb{R}^d$ -valued stochastic process defined by

$$(2.2) \quad \begin{cases} \nu_+(n) & \equiv X(n) - P_{M_0^{n-1}(X)} X(n) & (n \in \mathbb{N}^*) \\ \nu_-(-n) & \equiv X(-n) - P_{M_{-n+1}^0(X)} X(-n) & (n \in \mathbb{N}^*), \end{cases}$$

where $M_0^{-1}(X) = M_1^0(X) = \{0\}$ and $P_{M_0^{n-1}(X)}$ (resp. $P_{M_{-n+1}^0(X)}$) stands for the orthogonal projection on the space $M_0^{n-1}(X)$ (resp. $M_{-n+1}^0(X)$). In particular, it holds

that

$$(2.3) \quad \nu_+(0) = \nu_-(0) = X(0)$$

$$(2.4) \quad \text{The stochastic processes } \nu_{\pm} \text{ are orthogonal with mean vector zero}$$

$$(2.5) \quad M_0^n(X) = M_0^n(\nu_+) \quad \text{and} \quad M_{-n}^0(X) = M_{-n}^0(\nu_-) \quad (n \in \mathbb{N}^*).$$

As stated as in §1, the stochastic process X satisfies the forward (resp. the backward) KM_2O -Langevin equation (1.5₊) (resp. (1.5₋)). The dissipation-dissipation theorem (1.7_±) and the fluctuation-dissipation theorem (1.9_±)-(1.11) hold among the KM_2O -Langevin data.

On the other hand, the fundamental quantities $\delta_{\pm}(\cdot)$ can be calculated from the covariance matrix function R by the following algorithm:

Partial Autocorrelation Coefficient ([3],[1],[10],[11],[4]). For any $n \in \mathbb{N}$,

$$(2.6_{\pm}) \quad \delta_{\pm}(n) = -\{R(\pm n) + \sum_{k=0}^{n-2} \gamma_{\pm}(n-1, k) R(\pm(k+1))\} V_{\mp}(n-1)^{-1}.$$

Now we shall take eleven steps to prove Fluctuation-Fluctuation Theorem .

(Step 1) We claim that Burg's relation (1.12) is equivalent to a special case of the fluctuation-fluctuation theorem: for any $m \in \mathbb{N}$,

$$I(m, 1) = I(1, m).$$

Multiplying both-hand sides of equation (1.5₊) with $n = m$ by ${}^tX(-1)$ from the right and taking an expectation with respect to the probability measure P , we have

$$(2.7) \quad R(m+1) = - \sum_{k=0}^{m-1} \gamma_+(m, k) R(k+1) + E(\nu_+(m) {}^tX(-1)).$$

Since it follows from the weak stationarity of X that $R(m+1) = E(X(m) {}^tX(-1)) = E(X(1) {}^tX(-m))$, similarly, we multiply both-hand sides of equation (1.5₋) with $n = m$ by $X(1)$ from the left to obtain

$$(2.8) \quad R(m+1) = - \sum_{k=0}^{m-1} R(k+1) {}^t\gamma_-(m, k) + E(X(1) {}^t\nu_-(-m)).$$

Therefore, we apply Burg's relation (1.12) to (2.7) and (2.8) to obtain

$$(2.9) \quad E(\nu_+(m)^t X(-1)) = E(X(1)^t \nu_-(-m)).$$

On the other hand, it follows immediately from (1.5 $_{\pm}$) and (2.3)–(2.5) that

$$(2.10) \quad E(\nu_+(m)^t X(-1)) = I(m, 1) \text{ and } E(X(1)^t \nu_-(-m)) = I(1, m).$$

Hence Step 1 follows from (2.9) and (2.10).

(Step 2) We claim that for any $m \in \mathbb{N}$,

$$I(m, 1) = I(1, m) = -\delta_+(m+1)V_-(m).$$

Immediately from (2.6 $_+$), we have

$$R(m+1) = -\sum_{k=0}^{m-1} \gamma_+(m, k)R(k+1) - \delta_+(m+1)V_-(m),$$

which with (2.7) and (2.10) gives Step 2.

(Step 3) We claim that for any $n \in \mathbb{N}$,

$$(i) \quad V_+(n) = R(0) + \sum_{k=0}^{n-1} R(n-k)^t \gamma_+(n, k)$$

$$(ii) \quad V_-(n) = R(0) + \sum_{k=0}^{n-1} \gamma_-(n, k)^t R(n-k).$$

These follow immediately from (4.5) and (4.6) in the proof of Lemma 4.2 in [4]. Actually Step 3 can be proved from multiplying both-hand sides of equations (1.5 $_{\pm}$) by $^t X(\pm n)$ from the right, taking an expectation with respect to P and using (2.3)–(2.5).

(Step 4) For any $m, n \in \mathbb{N}^*$, put

$$(2.11) \quad F_n(m) \equiv R(n) + \sum_{k=1}^m \gamma_-(m, m-k)R(n+k).$$

Immediately from (ii) in Step 3, we have

$$F_0(m) = V_-(m).$$

(Step 5) We claim that for any $m, n \in \mathbb{N}$,

$$R(m+n) = - \sum_{k=1}^n \delta_+(m+k) F_{n-k}(m+k-1) - \sum_{k=0}^{m-1} \gamma_+(m, k) R(k+n).$$

We shall prove Step 5 by mathematical induction. By (2.6₊), we have

$$R(m+n) = -\delta_+(m+n) V_-(m+n-1) - \sum_{k=0}^{m+n-2} \gamma_+(m+n-1, k) R(k+1).$$

In particular, it follows from Step 4 that Step 5 holds for any $m \in \mathbb{N}$ and $n = 1$. Let n_0 be any natural number greater than or equal to 2 and assume that Step 5 holds for any $m \in \mathbb{N}$ and $n = n_0 - 1$. It then follows that

$$\begin{aligned} (2.12) \quad R(m+n_0) &= R((m+1) + (n_0-1)) = \\ &= - \sum_{k=1}^{n_0-1} \delta_+(m+k) F_{n_0-1-k}(m+k) - \sum_{k=0}^m \gamma_+(m+1, k) R(k+n_0-1). \end{aligned}$$

By relation (1.7₊) in the dissipation-dissipation theorem, we have

$$\begin{aligned} (2.13) \quad & \sum_{k=0}^m \gamma_+(m+1, k) R(k+n_0-1) \\ &= \delta_+(m+1) F_{n_0}(m) + \sum_{k=0}^{m-1} \gamma_+(m, k) R(k+n_0). \end{aligned}$$

Therefore, we see from (2.12) and (2.13) that Step 5 holds for any $m \in \mathbb{N}$ and $n = n_0$. Hence, we can prove Step 5.

(Step 6) We claim that for any $m, n \in \mathbb{N}$,

$$E(\nu_+(m)^t X(-n)) = - \sum_{k=1}^n \delta_+(m+k) F_{n-k}(m+k-1).$$

Multiplying both-hand sides of equation (1.5₊) with $n = m$ by ${}^t X(-n)$ from the right and taking an expectation with respect to P , we have

$$R(m+n) = - \sum_{k=0}^{m-1} \gamma_+(m, k) R(k+n) + E(\nu_+(m)^t X(-n)),$$

which with Step 5 yields Step 6.

(Step 7) We claim that for any $m, n \in \mathbb{N}, m \geq 2$,

$$F_{n-1}(m) = F_{n-1}(m-1) + \delta_-(m)E(\nu_+(m-1)^t X(-n)).$$

Applying (1.7_-) to each term $\gamma_-(m, m-k)$ ($1 \leq k \leq m-1$) in the definition of $F_{n-1}(m)$, we have

$$\begin{aligned} F_{n-1}(m) &= R(n-1) + \delta_-(m)R(n-1+m) + \\ &\quad + \sum_{k=1}^{m-1} (\gamma_-(m-1, m-1-k) + \delta_-(m)\gamma_+(m-1, k-1))R(n-1+k) \\ &= F_{n-1}(m-1) + \delta_-(m)\{R(n-1+m) + \sum_{\ell=0}^{m-2} \gamma_+(m-1, \ell)R(n+\ell)\} \\ &= F_{n-1}(m-1) - \delta_-(m)\left\{\sum_{k=1}^n \delta_+(m-1+k)F_{n-k}(m+k)\right\}. \end{aligned}$$

Hence, Step 7 follows from Step 6.

(Step 8) We claim that for any $m, n \in \mathbb{N}, m \geq 2$,

$$\begin{aligned} E(\nu_+(m)^t X(-n)) &= E(\nu_+(m+1)^t X(-n+1)) - \\ &\quad - \delta_+(m+1)\left\{\sum_{k=2}^m \delta_-(k)E(\nu_+(k-1)^t X(-n))\right\} - \delta_+(m+1)F_{n-1}(1). \end{aligned}$$

By Step 6, we have

$$E(\nu_+(m)^t X(-n)) = E(\nu_+(m+1)^t X(-n+1)) - \delta_+(m+1)F_{n-1}(m).$$

Hence, a repeat substitution of this into Step 7 yields Step 8.

(Step 9) We claim that for any $m, n \in \mathbb{N}, m, n \geq 2$,

$$\begin{aligned} E(\nu_+(m)^t \nu_-(-n)) &= E(\nu_+(m+1)^t X(-n+1)) - \\ &\quad - \delta_+(m+1)\left\{\sum_{k=2}^m \delta_-(k)E(\nu_+(k-1)^t \nu_-(-n))\right\} - \delta_+(m+1)F_{n-1}(1) + \\ &\quad + \sum_{\ell=1}^{n-1} \{E(\nu_+(m+1)^t X(-\ell+1)) - \delta_+(m+1)F_{\ell-1}(1)\}^t \gamma_-(n, \ell). \end{aligned}$$

Substituting the right-hand side of equation (1.5₋) into the term $X(-n)$ of both-hand sides in Step 8, we have

$$\begin{aligned} E(\nu_+(m)^t \nu_-(-n)) &= E(\nu_+(m+1)^t X(-n+1)) - \\ &\quad - \delta_+(m+1) \left\{ \sum_{k=2}^m \delta_-(k) E(\nu_+(k-1)^t \nu_-(-n)) \right\} - \delta_+(m+1) F_{n-1}(1) + \\ &\quad + \sum_{\ell=1}^{n-1} \left\{ E(\nu_+(m)^t X(-\ell)) + \delta_+(m+1) \left(\sum_{k=2}^m \delta_-(k) E(\nu_+(k-1)^t X(-\ell)) \right) \right\}^t \gamma_-(n, \ell). \end{aligned}$$

On the other hand, it follows from Step 8 that

$$\begin{aligned} &\text{the coefficient of } {}^t\gamma_-(n, \ell) \text{ in the relation above} \\ &= E(\nu_+(m+1)^t X(-\ell+1)) - \delta_+(m+1) F_{\ell-1}(1). \end{aligned}$$

Hence, we have Step 9.

(Step 10) We claim that for any $m, n \in \mathbb{N}, n \geq 2$,

$$\begin{aligned} &E(\nu_+(m+1)^t X(-n+1)) + \sum_{\ell=1}^{n-1} E(\nu_+(m+1)^t X(-\ell+1))^t \gamma_-(n, \ell) \\ &= E(\nu_+(m+1)^t \nu_-(-n+1)) + \sum_{k=1}^{n-2} E(\nu_+(m+1)^t \nu_-(-k))^t (\delta_-(n) \delta_+(k+1)). \end{aligned}$$

It is easy to see from (2.3)–(2.5) and (2.20) that Step 10 holds for $n = 2$. Let $n \geq 3$. By equation (1.5₋) with $n = n - 1$ and (1.7₋), we have

the upper-hand side in Step 10

$$\begin{aligned} &= E(\nu_+(m+1)^t \nu_-(-(n-1))) + \sum_{k=0}^{n-2} E(\nu_+(m+1)^t X(-k))^t (\gamma_-(n, k+1) - \gamma_-(n-1, k)) \\ &= E(\nu_+(m+1)^t \nu_-(-(n-1))) + E(\nu_+(m+1)^t X(-(n-2)))^t (\delta_-(n) \delta_+(n-1)) + \\ &\quad + \sum_{k=0}^{n-3} E(\nu_+(m+1)^t X(-k))^t (\delta_+(n) \gamma_+(n-1, n-k-2)). \end{aligned}$$

By using equation (1.5₋) with $n = n - 2$ and (1.7₋) again, we have

the upper-hand side in Step 10

$$\begin{aligned}
&= E(\nu_+(m+1)^t \nu_-(-(n-1))) + E(\nu_+(m+1)^t \nu_-(-(n-2)))^t (\delta_-(n) \delta_+(n-1)) + \\
&\quad + \sum_{k=0}^{n-3} E(\nu_+(m+1)^t X(-k))^t \{ \delta_+(n) (\gamma_+(n-1, n-k-2) -) - \delta_+(n-1) \gamma_-(n-2, k) \} \\
&= E(\nu_+(m+1)^t \nu_-(-(n-1))) + E(\nu_+(m+1)^t \nu_-(-(n-2)))^t (\delta_-(n) \delta_+(n-1)) + \\
&\quad + E(\nu_+(m+1)^t X(-(n-3)))^t (\delta_-(n) \delta_+(n-2)) + \\
&\quad + \sum_{k=0}^{n-4} E(\nu_+(m+1)^t X(-k))^t (\delta_-(n) \gamma_+(n-2, n-k-3)).
\end{aligned}$$

Hence, repeating the same prodedure, we can prove Step 10.

(Step 11) We claim that for any $n \in \mathbb{N}, n \geq 2$,

$$F_{n-1}(1) + \sum_{\ell=1}^{n-1} F_{\ell-1}(1)^t \gamma_-(n, \ell) = 0.$$

Since it follows from the definition of $F_m(n)$ that for any $m \in \mathbb{N}$,

$$F_m(1) = R(m) + \delta_-(1) R(m+1),$$

we have

$$(2.14) \quad F_{n-1}(1) + \sum_{\ell=1}^{n-1} F_{\ell-1}(1)^t \gamma_-(n, \ell) = I + \delta_-(1) II,$$

where

$$I = R(n-1) + \sum_{\ell=1}^{n-1} R(\ell-1)^t \gamma_-(n, \ell)$$

and

$$II = R(n) + \sum_{\ell=1}^{n-1} R(\ell)^t \gamma_-(n, \ell).$$

We shall show

$$(2.15) \quad II = -R(0)^t \delta_-(n).$$

By (1.7₋) and (2.6₋),

$$\begin{aligned} II &= -V_+(n-1)^t \delta_-(n) + \sum_{\ell=1}^{n-1} R(\ell)^t (\gamma_-(n, \ell) - \gamma_-(n-1, \ell-1)) \\ &= -\{V_+(n-1) - \sum_{\ell=1}^{n-1} R(\ell)^t \gamma_+(n-1, n-\ell-1)\}^t \delta_-(n). \end{aligned}$$

Hence, (2.15) follows from (i) in Step 3.

Further we shall show

$$(2.16) \quad I = R(0)^t \delta_+(1)^t \delta_-(n).$$

When $n = 2$, it follows from (1.7₋) and (2.6₊) that

$$\begin{aligned} I &= R(1) + R(0)^t \gamma_-(2, 1) \\ &= -\delta_+(1) R(0) + R(0)^t (\delta_-(1) + \delta_-(2) \delta_+(1)). \end{aligned}$$

Hence, by (1.10), we see that (2.16) holds for $n = 2$.

Let $n \geq 3$. By (1.7₋) and (2.6₋),

$$I = -V_+(n-2)^t \delta_-(n-1) - \sum_{k=0}^{n-3} R(k+1)^t \gamma_-(n-2, k) - \sum_{\ell=1}^{n-1} R(\ell-1)^t \gamma_-(n, \ell).$$

Applying (1.7₋) to the third term in the right-hand side of the relation above, we have

$$\begin{aligned} I &= -V_+(n-2)^t \delta_-(n-1) + R(0)^t \delta_-(n-1) + \\ &\quad + \sum_{k=0}^{n-3} R(k+1)^t (\gamma_-(n-1, k+1) - \gamma_-(n-2, k)) + \\ &\quad + \sum_{\ell=1}^{n-1} R(\ell-1)^t \gamma_-(n-1, n-\ell-1)^t \delta_-(n). \end{aligned}$$

By using (1.7₋) again, we have

$$\begin{aligned} (2.17) \quad I &= -\{V_+(n-2) - R(0) - \sum_{k=0}^{n-3} R(k+1)^t \gamma_+(n-2, n-k-3)\}^t \delta_-(n-1) + \\ &\quad + \sum_{\ell=1}^{n-1} R(\ell-1)^t \gamma_-(n-1, n-\ell-1)^t \delta_-(n). \end{aligned}$$

It follows from (i) in Step 3 that

$$(2.18) \quad \text{the coefficient of } {}^t\delta_-(n-1) \text{ in (2.17)} = 0.$$

Furthermore, we claim

$$(2.19) \quad \text{the coefficient of } {}^t\delta_-(n) \text{ in (2.17)} = R(0){}^t\delta_+(1).$$

By (1.7₊),

$$\begin{aligned} & \text{the coefficient of } {}^t\delta_-(n) \text{ in (2.17)} \\ &= \sum_{k=0}^{n-3} R(k){}^t\gamma_+(n-2, n-3-k) + \{R(n-2) + \sum_{k=0}^{n-3} R(k){}^t\gamma_-(n-2, k)\}{}^t\delta_+(n-1). \end{aligned}$$

On the other hand, by (3.5)₀ in [4], we get

$$R(n-2) = - \sum_{k=0}^{n-3} R(k){}^t\gamma_-(n-2, k),$$

which results from multiplying both-hand sides of equation (1.5₋) with $n = n-2$ by ${}^tX(0)$ from the right and taking an expectation with respect P . Therefore, we get

$$\text{the coefficient of } {}^t\delta_-(n) \text{ in (2.17)} = \sum_{k=0}^{n-3} R(k){}^t\gamma_+(n-2, n-3-k).$$

By repeating the same procedure and using (1.7₊), (1.10) and (2.6₊), we can show that

$$\begin{aligned} \text{the coefficient of } {}^t\delta_-(n) \text{ in (2.17)} &= \sum_{k=0}^1 R(k){}^t\gamma_+(2, 1-k) \\ &= R(0){}^t(\delta_+(1) + \delta_+(2)\delta_-(1)) - \delta_+(1)R(0)\delta_+(2) \\ &= R(0){}^t\delta_+(1) \end{aligned}$$

and so (2.19) holds.

Hence, (2.16) follows from (2.17)–(2.19). Consequently, we see from (2.14)–(2.16) that Step 11 holds.

(Step 12) We are now in the final position to prove Fluctuation-Fluctuation Theorem. (i) and (ii) follow from (2.3)-(2.5). (iii) has been proved in Step 2. By Step 9 and Step 10, we have

$$\begin{aligned}
& I(m, n) \\
&= I(m+1, n-1) + \left\{ \sum_{k=1}^{n-2} I(m+1, k)^t \delta_+(k+1) \right\}^t \delta_-(n) - \\
& \quad - \delta_+(m+1) \left\{ \sum_{k=2}^m \delta_-(k) I(k-1, n) \right\} - \delta_+(m+1) \left\{ F_{n-1}(1) + \sum_{l=1}^{n-1} F_{l-1}(1)^t \gamma_-(n, l) \right\}.
\end{aligned}$$

Hence, by virtue of Step 11, (iv) holds

Thus we complete the proof of Fluctuation-Fluctuation Theorem. (Q.E.D.)

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