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THE MORPHING OF FLUID QUEUES INTO MARKOV-MODULATED BROWNIAN MOTION

BY GUY LATOUCHE AND GIANG T. NGUYEN*

Ramaswami showed recently that standard Brownian motion arises as the limit of a family of Markov-modulated linear fluid processes. We pursue this analysis with a fluid approximation for Markov-modulated Brownian motion. We follow a Markov-renewal approach and we prove that the stationary distribution of a Markov-modulated Brownian motion reflected at zero is the limit from the well-analyzed stationary distribution of approximating linear fluid processes. Thus, we provide a new approach for obtaining the stationary distribution of a reflected MMBM without time-reversal or solving partial differential equations. Our results open the way to the analysis of more complex Markov-modulated processes.

Key matrices in the limiting stationary distribution are shown to be solutions of a matrix-quadratic equation, and we describe how this equation can be efficiently solved.

1. Introduction. Our purpose is to construct and analyse a family of fluid queues converging to Markov-modulated Brownian motion (MMBM) with the intention of adapting, to the analysis of MMBM, tools and methods which have been developed in the context of fluid queues.

Fluid queues are two-dimensional processes $\{X(t), \varphi(t) : t \geq 0\}$, where $\{\varphi(t) : t \geq 0\}$ is a continous-time Markov chain on a finite state space $\mathcal{M}$,

$$X(t) = X(0) + \int_0^t c_{\varphi(t)} \, \mathrm{d}t,$$

and c_i for $i \in \mathcal{M}$ are arbitrary real numbers. These are also known as *Markov-modulated linear fluid processes*, with X referred to as the *fluid level* and φ as the *phase*: during intervals of time where the phase φ remains in

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some state $i \in \mathcal{M}$, the fluid level varies linearly at the rate c_i. The associated process reflected at zero is denoted by $\{\widehat{X}(t), \varphi(t) : t \geq 0\}$, where

$$\widehat{X}(t) = X(t) - \inf_{0 \leq v \leq t} X(v),$$

assuming that $\widehat{X}(0) = 0$. Also referred to as first-order fluid processes, these stochastic models are useful when the relevant rates of change can be well-described by their first moments.

Markov-modulated Brownian motion (MMBM), or the family of second-order fluid processes, takes into account first and second moments of the rates of change. In particular, the fluid level $Y(t)$ of a Markov-modulated Brownian motion $\{Y(t), \kappa(t) : t \geq 0\}$ is a Brownian motion with drift μ_i and variance σ_i^2 during time intervals where $\kappa(t) = i$; one sometimes writes that

$$Y(t) = Y(0) + \int_0^t c_{\kappa(t)} \, \mathrm{d}t + \int_0^t \sigma_{\kappa(t)} \, \mathrm{d}W(t)$$

where $\{W(t)\}$ is a standard Brownian motion.

Three papers appeared in close succession on the stationary distribution of MMBM reflected at zero: Rogers [30], Asmussen [5], and Karandikar and Kulkarni [23]. The focus in the third paper is on solving partial differential equations, and it is not of further concern to us in the present paper. In [5, 30], on the other hand, the authors obtain the stationary distribution in a form which is suitable for calculations with linear algebraic procedures. These results crucially depend on the technique of reversing time, a method already used in Loynes [26] whereby the stationary conditional distribution of the level, given the phase, is obtained from the distribution of the maximum of a random walk with negative drift. More recent work for obtaining the stationary distribution of Markov-modulated Lévy processes with reflecting boundaries, as in Asmussen and Kella [6], Ivanovs [22], D'Auria *et al.* [16], and D'Auria and Kella [17], also uses the reverse-time approach.

For fluid processes without a Brownian component, another line of investigation was open in Ramaswami [28], based on renewal-type arguments similar to the ones used in the analysis of quasi-birth-and-death processes (Neuts [27, Chapter 3], Latouche and Ramaswami [25, Chapter 6]). This eventually led, in addition to interesting algorithmic procedures, to theoretical developments as in Ahn and Ramaswami [1] for fluid processes in finite time, da Silva Soares and Latouche [15] for systems with interaction between phase and level, and Bean and O'Reilly [7] where the phase takes value in a non-denumerable space, to cite but three examples. In this approach, the flow of time is not reversed and this creates a significant difference in the methods of analysis, in particular, one directly determines the joint distribution of the level and the phase.

Our intention is to establish a link between the results for fluid queues and those for MMBM. In Section 2, we extend the argument from Ramaswami [29] and define a parameterised family of linear fluid processes that converge weakly, as the parameter tends to infinity, to a Markov-modulated Brownian motion. Ahn and Ramaswami [2] are independently using matrix-analytic methods to analyze Markov-modulated Brownian motions, with different approaches to ours. We determine in Section 3 the limiting structure of key matrices and quadratic matrix equations, and we establish the connection between the stationary distribution so obtained, and the one which follows from the time-reversed approach. We present in Section 4 a computational procedure for solving the quadratic equation efficiently.

2. Markov-modulated Brownian motion. We show here that a family of linear fluid processes converges weakly to a Markov-modulated Brownian motion $\{Y(t), \kappa(t) : t \geq 0\}$, where the phase process κ is a Markov chain with state space $\mathcal{M} = \{1, \ldots, m\}$, and Y is a Brownian motion with drift μ_i and variance σ_i^2 whenever $\kappa(t) = i \in \mathcal{M}$. We denote by D the drift matrix $\mathrm{diag}(\mu_1, \ldots, \mu_m)$, by V the variance matrix $\mathrm{diag}(\sigma_1^2, \ldots, \sigma_m^2)$, and by Q the generator of κ, and we assume that Q is irreducible.

ASSUMPTION 2.1. *At time 0, the level $Y(0)$ is equal to 0, and the initial phase $\kappa(0)$ has the stationary distribution $\boldsymbol{\alpha}$ of Q ($\boldsymbol{\alpha} Q = \mathbf{0}$ and $\boldsymbol{\alpha}\mathbf{1} = 1$).*

Formally, for $t \geq 0$ the process $Y(t)$ can be defined recursively as

$$Y(t) = Y(T) + \sum_{i \in \mathcal{M}} \mathbb{1}_{\{\kappa(T)=i\}}(Y_i(t) - Y_i(T)), \tag{1}$$

where $Y(0) = 0$, the random variable T is the last jump epoch of κ before t ($T = 0$ if there has yet to be a jump), the process Y_i is a Brownian motion with mean μ_i and variance σ_i^2, and $\mathbb{1}_{\{\cdot\}}$ denotes the indicator function. The processes Y_i for all $i \in \mathcal{M}$ and the process κ are assumed to be mutually independent.

We construct the family of fluid processes $\{L_\lambda(t), \beta_\lambda(t), \varphi_\lambda(t) : t \geq 0\}$ as follows: the phase process is a two-dimensional Markov chain $(\beta_\lambda(t), \varphi_\lambda(t))$ with state space $\mathcal{S} = \{(k, i) : k \in \{1, 2\}$ and $i \in \mathcal{M}\}$ and generator

$$T_\lambda = \begin{bmatrix} Q - \lambda I & \lambda I \\ \lambda I & Q - \lambda I \end{bmatrix},$$

where the entries of T_λ follow the lexicographic ordering of $\{1,2\}\times\mathcal{M}$, and I denotes an appropriately-sized identity matrix. Whenever ambiguity might arise, we write I_n to denote the $n\times n$ identity matrix. The fluid rate matrix C_λ is given by

$$C_\lambda = \begin{bmatrix} D+\sqrt{\lambda}\Theta & \\ & D-\sqrt{\lambda}\Theta \end{bmatrix}, \quad \text{where } \Theta=\sqrt{V}.$$

ASSUMPTION 2.2. *At time* 0*, the level* $L_\lambda(0)$ *is equal to* 0*, and the initial phases* $\beta_\lambda(0)$ *and* $\varphi_\lambda(0)$ *have their respective stationary distributions* $\boldsymbol{\gamma}=(1/2,1/2)$ *and* $\boldsymbol{\alpha}$*, their joint distribution is* $\boldsymbol{p}=\boldsymbol{\gamma}\otimes\boldsymbol{\alpha}$*.*

Intuitively speaking, we duplicate the state space $\mathcal{M}$ in the Markov-modulated Brownian motion $\{Y(t),\kappa(t)\}$, and the auxiliary process $\beta_\lambda(t)$ is there to keep track of which copy is in use. Note that for λ sufficiently large, the phases in the copy with $\beta_\lambda(t)=1$ have all positive rates while the phases in the other copy have all negative rates. With this construction, we show that the conditional moment generating function of $\{L_\lambda(t),\varphi_\lambda(t)\}$ converges to that of $\{Y(t),\kappa(t)\}$.

Denote by $\Delta_Y(s)$ the $m\times m$ Laplace matrix exponent of $\{Y(t),\kappa(t)\}$, by $\tilde{\Delta}_\lambda(s)$ the $2m\times 2m$ Laplace matrix exponent of $\{L_\lambda(t),\beta_\lambda(t),\varphi_\lambda(t)\}$, and by $\Delta_\lambda(s)$ the $m\times m$ Laplace matrix exponent of $\{L_\lambda(t),\varphi_\lambda(t)\}$. These matrices are such that

$$[e^{\Delta_Y(s)t}]_{ij} = \mathrm{E}[e^{sY(t)}\mathbb{1}_{\{\kappa(t)=j\}}|Y(0)=0,\kappa(0)=i],$$
$$[e^{\tilde{\Delta}_\lambda(s)t}]_{(k,i)(k',j)} = \mathrm{E}[e^{sL_\lambda(t)}\mathbb{1}_{\{\beta_\lambda(t)=k',\varphi_\lambda(t)=j\}}|L_\lambda(0)=0,\beta_\lambda(0)=k,\varphi_\lambda(0)=i],$$

and

$$[e^{\Delta_\lambda(s)t}]_{ij} = \mathrm{E}[e^{sL_\lambda(t)}\mathbb{1}_{\{\varphi_\lambda(t)=j\}}|L_\lambda(0)=0,\varphi_\lambda(0)=i]. \tag{2}$$

By Asmussen and Kella [6], the Laplace matrix exponent of a Markov-modulated Lévy process $\{Z(t),\xi(t)\}$ with jumps is given by

$$\Delta_Z(s) = \mathrm{diag}(\phi_1(s),\ldots,\phi_m(s)) + Q\circ R(s),$$

where $\phi_i(s)$ is the Laplace exponent of an unmodulated Lévy process with parameters defined for phase $i\in\{1,\ldots,m\}$, Q is the phase-transition matrix of $\xi(t)$, R is the matrix with components $[R(s)]_{ij}=\mathrm{E}[e^{sW_{ij}}]$, which are the Laplace transforms of the jumps W_{ij} for $Z(t)$ when $\xi(t)$ moves from i to j, and $\circ$ indicates the Hadamard product.

As the Laplace exponent of an unmodulated Brownian motion with drift μ and variance σ^2 is given by $\mu s + \sigma^2 s^2/2$, one can verify that

$$\begin{aligned}\Delta_Y(s) &= sD + (s^2/2)V + Q,\\ \tilde{\Delta}_\lambda(s) &= sC_\lambda + T_\lambda\\ &= I \otimes M + s\sqrt{\lambda} J \otimes \Theta + \lambda G \otimes I,\end{aligned}$$

where

$$M = sD + Q, \qquad J = \begin{bmatrix} 1 & \\ & -1 \end{bmatrix} \qquad \text{and} \qquad G = \begin{bmatrix} -1 & 1 \\ 1 & -1 \end{bmatrix},$$

and

$$e^{\Delta_\lambda(s)t} = (\boldsymbol{\gamma} \otimes I) e^{\tilde{\Delta}_\lambda(s)t} (\mathbf{1} \otimes I), \tag{3}$$

where $\mathbf{1}$ is an appropriately-sized column vector of ones.

The next lemma gives a technical property of the matrix exponential, it is used in the proof of Theorem 2.4.

Lemma 2.3. *Let S be the block-partitioned matrix*

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$$

where S_{11} and S_{22} are matrices of order m_1 and m_2, respectively. Denote by $H(t)$ the north-west quadrant of order m_1 of e^{St}:

$$H(t) = \begin{bmatrix} I_{m_1 \times m_1} & 0 \end{bmatrix} e^{St} \begin{bmatrix} I_{m_1 \times m_1} \\ 0 \end{bmatrix}.$$

The matrix $H(t)$ is the solution of

$$H(t) = e^{S_{11}t} + \int_0^t \int_v^t e^{S_{11}(t-u)} S_{12} e^{S_{22}(u-v)} S_{21} H(v) \, \mathrm{d}u \, \mathrm{d}v. \tag{4}$$

Proof. We decompose S as the sum $S = S_A + S_E$, with

$$S_A = \begin{bmatrix} S_{11} & S_{12} \\ 0 & S_{22} \end{bmatrix} \qquad \text{and} \qquad S_E = \begin{bmatrix} 0 & 0 \\ S_{21} & 0 \end{bmatrix} = \begin{bmatrix} 0 \\ I \end{bmatrix} S_{21} \begin{bmatrix} I & 0 \end{bmatrix}.$$

By Higham [21, Equations (10:13) and (10:40)], we obtain

$$e^{St} = e^{S_A t} + \int_0^t e^{S_A(t-v)} S_E e^{S(v)} \, \mathrm{d}v.$$

and

$$e^{S_A t} = \begin{bmatrix} e^{S_{11}t} & \int_0^t e^{S_{11}(t-u)} S_{12} e^{S_{22}u} \, \mathrm{d}u \\ 0 & e^{S_{22}t} \end{bmatrix}$$

Thus,

$$\begin{aligned} H(t) &= \begin{bmatrix} I & 0 \end{bmatrix} e^{S_A t} \begin{bmatrix} I \\ 0 \end{bmatrix} + \int_0^t \begin{bmatrix} I & 0 \end{bmatrix} e^{S_A(t-v)} S_E e^{S(v)} \begin{bmatrix} I \\ 0 \end{bmatrix} \, \mathrm{d}v \\ &= e^{S_{11}t} + \int_0^t \begin{bmatrix} I & 0 \end{bmatrix} e^{S_A(t-v)} \begin{bmatrix} 0 \\ I \end{bmatrix} S_{21} \begin{bmatrix} I & 0 \end{bmatrix} e^{S(v)} \begin{bmatrix} I \\ 0 \end{bmatrix} \, \mathrm{d}v \\ &= e^{S_{11}t} + \int_0^t \int_0^{t-v} e^{S_{11}(t-v-u)} S_{12} e^{S_{22}u} S_{21} H(v) \, \mathrm{d}u \, \mathrm{d}v \end{aligned}$$

which proves (4). □

THEOREM 2.4. *The conditional moment generating function of* $\{L_\lambda(t), \varphi_\lambda(t)\}$ *converges to that of* $\{Y(t), \kappa(t)\}$, *that is,*

$$\lim_{\lambda \to \infty} (\boldsymbol{\gamma} \otimes I) e^{\tilde{\Delta}_\lambda(s)t} (\mathbf{1} \otimes I) = e^{\Delta_Y(s)t}. \tag{5}$$

PROOF. We proceed in three steps. First, we observe that

$$\tilde{\Delta}_\lambda^k(s)(\mathbf{1} \otimes I) = \mathbf{1} \otimes A_k + \boldsymbol{e} \otimes B_k, \qquad \text{for } k \geq 0, \tag{6}$$

where $\boldsymbol{e} = (1, -1)^{\mathrm{T}}$ and

$$\begin{bmatrix} A_k \\ B_k \end{bmatrix} = \Upsilon^k \begin{bmatrix} I \\ 0 \end{bmatrix}, \tag{7}$$

with

$$\Upsilon = \begin{bmatrix} M & s\sqrt{\lambda}\Theta \\ s\sqrt{\lambda}\Theta & M - 2\lambda I \end{bmatrix}.$$

The proof of (6) is by induction: that equation trivially holds for $k = 0$, with $A_0 = I$ and $B_0 = 0$ and, if it also holds for a given value of k, then we easily verify that $\tilde{\Delta}_\lambda^{k+1}(s)(\mathbf{1} \otimes I) = \mathbf{1} \otimes A_{k+1} + \boldsymbol{e} \otimes B_{k+1}$ with

$$A_{k+1} = M A_k + s\sqrt{\lambda}\Theta B_k, \qquad B_{k+1} = s\sqrt{\lambda}\Theta A_k + (M - 2\lambda I) B_k,$$

or

$$\begin{bmatrix} A_{k+1} \\ B_{k+1} \end{bmatrix} = \begin{bmatrix} M & s\sqrt{\lambda}\Theta \\ s\sqrt{\lambda}\Theta & M - 2\lambda I \end{bmatrix} \begin{bmatrix} A_k \\ B_k \end{bmatrix}.$$

Equation (7) readily follows.

To simplify the notation, we define $H_\lambda(t) = e^{\Delta_\lambda(s)t}$ for the remainder of the proof. By (3), we have

$$\begin{aligned} H_\lambda(t) &= \frac{1}{2}(\mathbf{1}^{\mathrm{T}} \otimes I)\sum_{k=0}^{\infty}\frac{t^k}{k!}\tilde{\Delta}_\lambda^k(s)(\mathbf{1}\otimes I) \\ &= \sum_{k\geq 0}\frac{t^k}{k!}A_k \qquad\qquad \text{from (6)} \\ &= \begin{bmatrix} I & 0\end{bmatrix} \exp \Upsilon t \begin{bmatrix} I \\ 0 \end{bmatrix}. \end{aligned}$$

By Lemma 2.3, $H_\lambda(t)$ is a solution of

$$H_\lambda(t) = e^{Mt} + s^2\lambda \int_0^t \left\{ \int_v^t e^{M(t-u)}\Theta e^{(M-2\lambda I)(u-v)}\,\mathrm{d}u \right\} \Theta H_\lambda(v)\,\mathrm{d}v. \tag{8}$$

Integrating by parts the inner integral, we find

$$\begin{aligned} &\lambda \int_v^t e^{M(t-u)}\Theta e^{(M-2\lambda I)(u-v)}\,\mathrm{d}u \\ &\quad = \Big[\lambda e^{M(t-u)}\Theta e^{(M-2\lambda I)(u-v)}(M-2\lambda I)^{-1}\Big]_v^t \\ &\qquad + \lambda \int_v^t M e^{M(t-u)}\Theta e^{(M-2\lambda I)(u-v)}(M-2\lambda I)^{-1}\,\mathrm{d}u \\ &\quad = \Theta e^{(M-2\lambda I)(t-v)}(1/\lambda M - 2I)^{-1} - e^{M(t-v)}\Theta(1/\lambda M - 2I)^{-1} \\ &\qquad + \int_v^t M e^{M(t-u)}\Theta e^{(M-2\lambda I)(u-v)}(1/\lambda M - 2I)^{-1}\,\mathrm{d}u, \end{aligned}$$

which converges to $1/2e^{M(t-v)}\Theta$ as $\lambda \to \infty$. From (8), we conclude that

$$H_\infty(t) = e^{Mt} + (s^2/2)\int_0^t e^{M(t-v)} V H_\infty(v)\,\mathrm{d}v,$$

and therefore

$$\frac{\mathrm{d}}{\mathrm{d}t}H_\infty(t) = (M + (s^2/2)V)H_\infty(t) = \Delta_Y(s)H_\infty(t).$$

This completes the proof. □

The Laplace matrix exponent uniquely characterizes the finite-dimensional distributions of the process and therefore Theorem 2.4 implies the following result.

COROLLARY 2.5. *The finite-dimensional distributions of $\{L_\lambda(t), \varphi_\lambda(t)\}$ converge to the finite-dimensional distributions of the Markov-modulated Brownian motion $\{Y(t), \kappa(t)\}$.* □

To conclude this section, we prove that the family $\{L_\lambda(t), \varphi_\lambda(t) : t \geq 0\}$ is tight; to that end, we construct as follows a representation of $L_\lambda(t)$ in terms of restricted processes, watched only when the phase φ_λ is constant (see Freedman [19, Section 1.5]). Define $\{t_n : n \geq 0\}$ as the successive epochs of change of phase, with $t_0 = 0$, and define $K = \sup\{n : t_n < t\}$. We may write

$$\begin{aligned} L_\lambda(t) &= L_\lambda(t_K) + \sum_{i \in \mathcal{M}} \mathbb{1}_{\{\varphi_\lambda(t_K)=i\}}(L_\lambda(t) - L_\lambda(t_K)) \\ &= \sum_{n=0}^{K-1} \sum_{i \in \mathcal{M}} \mathbb{1}_{\{\varphi_\lambda(t_n)=i\}}(L_\lambda(t_{n+1}) - L_\lambda(t_n)) \\ &\quad + \sum_{i \in \mathcal{M}} \mathbb{1}_{\{\varphi_\lambda(t_K)=i\}}(L_\lambda(t) - L_\lambda(t_K)) \\ &= \sum_{i \in \mathcal{M}} Z_\lambda^i(t), \end{aligned} \tag{9}$$

where

$$Z_\lambda^i(t) = \sum_{n=0}^{K-1} \mathbb{1}_{\{\varphi_\lambda(t_n)=i\}}(L_\lambda(t_{n+1}) - L_\lambda(t_n)) + \mathbb{1}_{\{\varphi_\lambda(t_K)=i\}}(L_\lambda(t) - L_\lambda(t_K)).$$

For each i, the process Z_λ^i is continuous, it varies like L_λ during the intervals of time when the phase is i and remains constant at all other time. Next, we associate a local clock to each phase and define the time spent in phase i during the interval $(0, t)$ as

$$\tau_i(t) = \sum_{n=0}^{K-1} \mathbb{1}_{\{\varphi_\lambda(t_n)=i\}}(t_{n+1} - t_n) + \mathbb{1}_{\{\varphi_\lambda(t_K)=i\}}(t - t_K). \tag{10}$$

Clearly, τ_i is continuous and remains constant over intervals when the phase is different from i. We also define $\rho_i(t) = \max\{s : \tau_i(s) = t\}$, thus, ρ_i is strictly increasing and continuous from the right. Finally, we define for each i the restricted process $\{L_\lambda^i(t), \beta_\lambda^i(t)\}$ with

$$L_\lambda^i(t) = Z_i(\rho_i(t)), \qquad \beta_\lambda^i(t)) = \beta_\lambda(\rho_i(t)).$$

Equation (9) may be written as

$$L_\lambda(t) = \sum_{i \in \mathcal{M}} L_\lambda^i(\tau_i(t)). \tag{11}$$

THEOREM 2.6. *The family $\{L_\lambda(t), \varphi_\lambda(t) : t \geq 0\}$ is tight.*

PROOF. By Billingsley [8, Theorem 7.3] we need to prove that the processes are tight at time 0, which is obviously true by Assumption 2.2, and that

$$\forall \varepsilon, \eta,\ \exists\, \delta^* > 0, \lambda^* \text{ s.t. } \mathrm{P}[\sup_{|s-t|\le\delta} |L_\lambda(t) - L_\lambda(s)| \ge \varepsilon] \le \eta \tag{12}$$

for all $\lambda > \lambda^*$ and $\delta < \delta^*$. By (11),

$$\begin{aligned}\sup_{|s-t|\le\delta} |L_\lambda(t) - L_\lambda(s)| &= \sup_{|s-t|\le\delta} |\sum_{i\in\mathcal{M}} (L^i_\lambda(\tau_i(t)) - L^i_\lambda(\tau_i(s)))| \\ &\le \sum_{i\in\mathcal{M}} \sup_{|s-t|\le\delta} |L^i_\lambda(\tau_i(t)) - L^i_\lambda(\tau_i(s))| \\ &\le \sum_{i\in\mathcal{M}} \sup_{|s-t|\le\delta} |L^i_\lambda(t) - L^i_\lambda(s)|,\end{aligned}$$

the last inequality being justified by the fact that $|\tau_i(s) - \tau_i(t)| \le |s-t|$. Therefore,

$$\begin{aligned}\mathrm{P}[\sup_{|s-t|\le\delta} |L_\lambda(t) - L_\lambda(s)| \ge \varepsilon] &\le \mathrm{P}[\sum_{i\in\mathcal{M}} \sup_{|s-t|\le\delta} |L^i_\lambda(t) - L^i_\lambda(s)| \ge \varepsilon] \\ &\le \mathrm{P}[\cup_{i\in\mathcal{M}}[\sup_{|s-t|\le\delta} |L^i_\lambda(t) - L^i_\lambda(s)| \ge \varepsilon/m]] \qquad (13) \\ &\le \sum_{i\in\mathcal{M}} \mathrm{P}[\sup_{|s-t|\le\delta} |L^i_\lambda(t) - L^i_\lambda(s)| \ge \varepsilon/m].\end{aligned}$$

Now, take a fixed i and reorganize the generator Q so that phase i occupies the first position:

$$Q = \begin{bmatrix} q_{ii} & \boldsymbol{d}_i \\ \boldsymbol{q}_i & Q_i \end{bmatrix}$$

where Q_i is a matrix of order $m-1$, and $\boldsymbol{d}_i$ and $\boldsymbol{q}_i$ are vectors of appropriate dimensions. The marginal distribution of $\{L^i_\lambda(t), \beta^i_\lambda(t)\}$ is that of a two-phases fluid queue with fluid rate matrix C^i_λ given by

$$C^i_\lambda = \begin{bmatrix} \mu_i + \sqrt{\lambda}\sigma_i & \\ & \mu_i - \sqrt{\lambda}\sigma_i \end{bmatrix},$$

and generator

$$T^i_\lambda = \begin{bmatrix} q_{ii} - \lambda & \lambda \\ \lambda & q_{ii} - \lambda \end{bmatrix} - \begin{bmatrix} \boldsymbol{d}_i & \\ & \boldsymbol{d}_i \end{bmatrix} \begin{bmatrix} Q_i - \lambda I & \lambda I \\ \lambda I & Q_i - \lambda I \end{bmatrix}^{-1} \begin{bmatrix} \boldsymbol{q}_i & \\ & \boldsymbol{q}_i \end{bmatrix}$$

(see [25, Theorem 5.5.3])

$$= \begin{bmatrix} q_{ii}-\lambda & \lambda \\ \lambda & q_{ii}-\lambda \end{bmatrix} + \begin{bmatrix} \boldsymbol{d}_i & \\ & \boldsymbol{d}_i \end{bmatrix} \begin{bmatrix} \boldsymbol{x} & \boldsymbol{1}-\boldsymbol{x} \\ \boldsymbol{1}-\boldsymbol{x} & \boldsymbol{x} \end{bmatrix}$$

where $\boldsymbol{x} = \boldsymbol{1} - \frac{1}{2}(I - \frac{1}{2\lambda}Q_i)^{-1}\boldsymbol{1}$, as one proves by direct verification. We eventually obtain that

$$T_\lambda^i = \begin{bmatrix} -\lambda-\nu_i & \lambda+\nu_i \\ \lambda+\nu_i & -\lambda-\nu_i \end{bmatrix}$$

with $\nu_i = \frac{1}{2}\boldsymbol{d}_i(I - \frac{1}{2\lambda}Q_i)^{-1}\boldsymbol{1}$; ν_i is the rate at which the process leaves phase i either with β_λ equal to 1 or 2, and returns to phase i with β_λ having the other value.

The proof of [29, Theorem 5] shows that for each $i \in \mathcal{M}$ the family of censored processes $\{L_\lambda^i\}$ is tight on any compact interval of $[0,\infty)$. By [33, Corollary 7], we can extend this result to show that the family of marginal processes $\{L_\lambda^i\}$ is tight on $[0,\infty)$. This implies that

$$\forall \varepsilon,\eta,\ \exists \delta_i(\varepsilon,\eta) > 0, \lambda_i(\varepsilon,\eta) \text{ s.t. } \mathrm{P}[\sup_{|s-t|\le\delta} |L_\lambda^i(t) - L_\lambda^i(s)| \ge \varepsilon] \le \eta \tag{14}$$

for all $\lambda > \lambda_i(\varepsilon,\eta)$ and $\delta < \delta_i(\varepsilon,\eta)$. We conclude that (12) holds by (13) if $\delta \le \delta_i(\varepsilon/m,\eta/m)$ and $\lambda > \lambda_i(\varepsilon/m,\eta/m)$ for all i, and the theorem is proved. $\square$

The next theorem follows from Corollary 2.5 and Theorem 2.6.

THEOREM 2.7. *The processes $\{L_\lambda(t),\varphi_\lambda(t) : t \ge 0\}$ converge weakly to the Markov-modulated Brownian motion $\{Y(t),\kappa(t) : t \ge 0\}$.* $\square$

3. Stationary distribution.

We consider again the Markov-modulated Brownian motion $\{Y(t),\kappa(t) : t \ge 0\}$ described in Section 2, but with a reflection at level zero. The reflected process is denoted as $\{\widehat{Y}(t),\kappa(t) : t \ge 0\}$, with

$$\widehat{Y}(t) = Y(t) - \inf_{0\le v\le t} Y(v).$$

Furthermore, we define the reflected fluid process $\{\widehat{L}_\lambda(t),\beta_\lambda(t),\varphi_\lambda(t) : t \ge 0\}$, where

$$\widehat{L}_\lambda(t) = L_\lambda(t) - \inf_{0\le v\le t} L_\lambda(v).$$

For notational convenience, we define $\varepsilon = 1/\sqrt{\lambda}$. With this, the reflected fluid process is written as $\{\widehat{L}_\varepsilon(t),\beta_\varepsilon(t),\varphi_\varepsilon(t) : t \ge 0\}$ and our purpose is to show that the stationary distribution of $\{\widehat{Y}(t),\kappa(t)\}$ is the limit, as $\varepsilon \to 0$, of the stationary distribution of the reflected fluid process $\{\widehat{L}_\varepsilon(t),\varphi_\varepsilon(t)\}$.

We emphasize that the processes $\{\widehat{L}_\lambda(t), \varphi_\lambda(t)\}$ and $\{\widehat{L}_\varepsilon(t), \varphi_\varepsilon(t)\}$ are the same. The change in subscripts only reflects the notational change in our perturbation parameter.

ASSUMPTION 3.1. *The mean drift $\boldsymbol{\alpha} D\mathbf{1}$ is strictly negative, so that all reflected processes are positive recurrent.*

ASSUMPTION 3.2. *The variance σ_i^2 is positive for all $i \in \mathcal{M}$. This assumption ensures the existence of Θ^{-1}, which we need later on.*

The following result is a direct corollary of Theorem 2.7, by the Skorokhod mapping theorem.

COROLLARY 3.3. *The processes $\{\widehat{L}_\varepsilon(t), \varphi_\varepsilon(t) : t \geq 0\}$ weakly converge as $\varepsilon \to 0$ to the reflected Markov-modulated Brownian motion $\{\widehat{Y}(t), \kappa(t) : t \geq 0\}$.* □

We denote the stationary distribution vector of $\{\widehat{L}_\varepsilon(t), \beta_\varepsilon(t), \varphi_\varepsilon(t)\}$ by $\boldsymbol{F}_\varepsilon(x)$ and the associated stationary density vector by $\boldsymbol{\pi}_\varepsilon(x)$, with components

$$[F_\varepsilon(x)]_{ki} = \lim_{t\to\infty} \mathrm{P}[\widehat{L}_\varepsilon(t) \leq x, \beta_\varepsilon(t) = k, \varphi_\varepsilon(t) = i],$$

and $[\pi_\varepsilon(x)]_{ki} = \mathrm{d}/\mathrm{d}x[F_\varepsilon(x)]_{ki}$, for $k \in \{1, 2\}$ and $i \in \mathcal{M}$, and we partition the generator and the fluid rate matrices as

$$T_\varepsilon = \begin{bmatrix} T_\varepsilon^{++} & T_\varepsilon^{+-} \\ T_\varepsilon^{-+} & T_\varepsilon^{--} \end{bmatrix} \qquad \text{and} \qquad C_\varepsilon = \begin{bmatrix} C_\varepsilon^{+} & 0 \\ 0 & C_\varepsilon^{-} \end{bmatrix},$$

where

$$\begin{aligned} T_\varepsilon^{++} &= T_\varepsilon^{--} = Q - (1/\varepsilon)^2 I, & C_\varepsilon^{+} &= D + (1/\varepsilon)\Theta, \\ T_\varepsilon^{+-} &= T_\varepsilon^{-+} = (1/\varepsilon)^2 I, & C_\varepsilon^{-} &= D - (1/\varepsilon)\Theta. \end{aligned}$$

We assume that ε is sufficiently small that the diagonal elements of C_ε^{+} are all positive, and those of C_ε^{-} are all negative, and we write $|C_\varepsilon^{-}|$ for the matrix of absolute values of the elements of C_ε^{-}.

Let $\xi_\varepsilon^{+}(x) = \inf\{t < \infty : L_\varepsilon(t) > x\}$ and $\xi_\varepsilon^{-}(x) = \inf\{t < \infty : L_\varepsilon(t) < x\}$ be the first passage times to the level x, respectively from below and from above, of the unbounded process L_ε. A key component of the stationary distribution of $\{\widehat{L}_\varepsilon(t), \beta_\varepsilon(t), \varphi_\varepsilon(t)\}$ is the matrix Ψ_ε of first passage probability from above, that is,

$$\begin{aligned} (\Psi_\varepsilon)_{ij} = \mathrm{P}[&\xi_\varepsilon^{-}(x) < \infty, \beta_\varepsilon(\xi_\varepsilon^{-}(x)) = 2, \varphi_\varepsilon(\xi_\varepsilon^{-}(x)) = j \\ &|L_\varepsilon(0) = x, \beta_\varepsilon(0) = 1, \varphi_\varepsilon(0) = i] \end{aligned}$$

for i and j in $\mathcal{M}$, and any level x. Similarly, Ψ_ε^* is the matrix of first passage probabilities from below, from $(x, 2, i)$ to $(x, 1, j)$, for i and j in $\mathcal{M}$.

The stationary distribution is given in the literature under various slightly different forms; here, we use the one from Govorun *et al.* [20, Theorem 2.1]:

$$\boldsymbol{F}_\varepsilon(0) = \begin{bmatrix}\mathbf{0} & \boldsymbol{\zeta}_\varepsilon\end{bmatrix}, \tag{15}$$

$$\boldsymbol{\pi}_\varepsilon(x) = \boldsymbol{\zeta}_\varepsilon T_\varepsilon^{-+} e^{K_\varepsilon x} \begin{bmatrix}(C_\varepsilon^+)^{-1} & \Psi_\varepsilon |C_\varepsilon^-|^{-1}\end{bmatrix} \qquad \text{for } x > 0, \tag{16}$$

where

$$K_\varepsilon = (C_\varepsilon^+)^{-1} T_\varepsilon^{++} + \Psi_\varepsilon |C_\varepsilon^-|^{-1} T_\varepsilon^{-+}, \tag{17}$$

and $\boldsymbol{\zeta}_\varepsilon$ is the unique solution of

$$\boldsymbol{\zeta}_\varepsilon (T_\varepsilon^{--} + T_\varepsilon^{-+} \Psi_\varepsilon) = \mathbf{0}, \tag{18}$$

$$\boldsymbol{\zeta}_\varepsilon \mathbf{1} + \boldsymbol{\zeta}_\varepsilon T_\varepsilon^{-+} (-K_\varepsilon)^{-1} \{(C_\varepsilon^+)^{-1} \mathbf{1} + \Psi_\varepsilon |C_\varepsilon^-|^{-1} \mathbf{1}\} = 1. \tag{19}$$

Probabilistically, $\boldsymbol{\zeta}_\varepsilon$ is up to a multiplicative constant the stationary distribution of the process censored at level 0, and $e^{K_\varepsilon x}$ is the matrix of expected number of crossings of level x in the various phases $(1, i)$, starting from level 0, before the first return to level 0.

In view of (16), we need to analyze Ψ_ε, K_ε and ζ_ε as $\varepsilon \to 0$, and it is obvious from (17) and (18, 19) that we should focus on the matrix Ψ_ε first. The next lemma is the key to our analysis. One might expect (20, 21) to have a simple proof but the one we have is lengthy and tedious. We place it in Appendix A to preserve the flow of the paper. Lemma 3.6 and Theorem 3.7 easily follow.

LEMMA 3.4. *For $\varepsilon \geq 0$,*

$$\Psi_\varepsilon = I + \varepsilon \Psi_1 + O(\varepsilon^2), \tag{20}$$

$$\Psi_\varepsilon^* = I + \varepsilon \Psi_1^* + O(\varepsilon^2), \tag{21}$$

where $\Theta^{-1}\Psi_1$ and $-\Theta^{-1}\Psi_1^*$ are both solutions to

$$X^2 + 2V^{-1} D X + 2V^{-1} Q = 0, \tag{22}$$

and are irreducible. Furthermore, the roots $\theta_1, \theta_2, \ldots, \theta_{2m}$ of the polynomial

$$\gamma(z) = \det(z^2 I + 2zV^{-1} D + 2V^{-1} Q)$$

associated to (22), numbered in increasing order of their real parts, satisfy the inequalities

$$Re(\theta_1) \leq \cdots \leq Re(\theta_{m-1}) < \theta_m = 0 < Re(\theta_{m+1}) \leq \cdots \leq Re(\theta_{2m}). \tag{23}$$

Finally, $\Theta^{-1}\Psi_1$ has one eigenvalue equal to zero and $m-1$ eigenvalues with strictly negative real parts, and it is the unique such solution; $-\Theta^{-1}\Psi_1^*$ has m eigenvalues with strictly positive real parts, and is the unique such solution. □

REMARK 3.5. Let $\tau_x^{\pm} = \inf\{t < \infty : \pm Y(t) > x\}$ be the first passage times to the corresponding levels x and $-x$ of the unbounded process $Y(t)$. Under Assumption 3.2 that $\sigma_i > 0$ for all $i \in \mathcal{M}$, it is easy to confirm that $\Theta^{-1}\Psi_1$ and $\Theta^{-1}\Psi_1^*$ are the same as, respectively, the generators Λ^- and Λ^+ of the time-changed processes $\kappa(\tau_x^-)$ and $\kappa(\tau_x^+)$ in Ivanovs [22], and $\Theta^{-1}\Psi_1^*$ is the same as the matrix $U(\gamma)$ for $\gamma = 0$ in Breuer [14].

By Lemma 3.4, the matrices Ψ_1 and Ψ_1^* are uniquely identified through (22). We now turn to the matrix K_ε, and to the matrix K_ε^* defined as

$$K_\varepsilon^* = |C_\varepsilon^-|^{-1}T_\varepsilon^{--} + \Psi_\varepsilon^*(C_\varepsilon^+)^{-1}T_\varepsilon^{+-}. \tag{24}$$

(this is the same definition as in (61)).

LEMMA 3.6. *For $\varepsilon \geq 0$,*

$$K_\varepsilon = K_0 + O(\varepsilon), \tag{25}$$

$$K_\varepsilon^* = K_0^* + O(\varepsilon), \tag{26}$$

where $K_0 = \Psi_1\Theta^{-1} + 2V^{-1}D$ and $K_0^* = \Psi_1^*\Theta^{-1} - 2V^{-1}D$. The matrices $-K_0$ and K_0^* are solutions of the equation

$$X^2 + 2XV^{-1}D + 2\Theta^{-1}Q\Theta^{-1} = 0, \tag{27}$$

and are irreducible. Furthermore, K_0 has m eigenvalues with strictly negative real parts, and it is the unique such solution; K_0^* has one eigenvalue equal to zero and $m-1$ eigenvalues with strictly negative real parts, and is the unique such solution.

PROOF. We write (17) as

$$\begin{aligned}\varepsilon K_\varepsilon &= -(\Theta + \varepsilon D)^{-1}(I - \varepsilon^2 Q) + \Psi_\varepsilon(\Theta - \varepsilon D)^{-1} \\ &= -(\Theta^{-1} - \varepsilon V^{-1}D + O(\varepsilon^2))(I - \varepsilon^2 Q) \\ &\quad + (I + \varepsilon\Psi_1 + O(\varepsilon^2))(\Theta^{-1} + \varepsilon V^{-1}D + O(\varepsilon^2))\end{aligned}$$

by (45), (46) and (20),

$$= \varepsilon(2V^{-1}D + \Psi_1\Theta^{-1}) + O(\varepsilon^2),$$

which proves (25); equation (26) follows in a similar manner. It is easy to verify that K_0 and $-K_0^*$ both satisfy (27), of which the associated polynomial is

$$\begin{aligned}\Xi(z) &= z^2 I + 2zV^{-1}D + 2\Theta^{-1}Q\Theta^{-1} \\ &= \Theta^{-1}\Gamma(z)\Theta^{-1} \qquad \text{with } \Gamma(z) \text{ defined in Proposition A.4} \\ &= (zI + K_0)\Theta(zI - \Theta^{-1}\Psi_1)\Theta^{-1}\end{aligned}$$

by (57), after some simple manipulations. This, together with Lemma 3.4, shows that the eigenvalues of $-K_0$ are the roots $\theta_{m+1}, \ldots, \theta_{2m}$ of $\gamma(z)$ with strictly positive real parts. Finally, using (58) we write

$$\Xi(z) = (zI - K_0^*)\Theta(zI + \Theta^{-1}\Psi_1^*)\Theta^{-1},$$

and conclude that the eigenvalues of K_0^* are the roots θ_1 to θ_m. Finally, as Ψ_1 and Ψ_1^* are irreducible, and Θ, V, and D are diagonal matrices, we conclude that K_0 and K_0^* are irreducible, and this completes the proof. $\square$

The next theorem states that the limit, as $\lambda \to \infty$, of the stationary distributions of the approximating fluid processes is indeed the stationary distribution of the limiting process $\{\widehat{Y}(t), \kappa(t)\}$. We prove this result by showing that the limiting distribution (28) coincides with the stationary distribution of $\{\widehat{Y}(t), \kappa(t)\}$ as obtained by Asmussen [5, Theorem 2.1 and Corollary 4.1].

THEOREM 3.7. *The limiting distribution of* $\{\widehat{L}_\lambda(t), \widehat{\varphi}_\lambda(t)\}$ *converges, as* λ *goes to infinity, to the stationary distribution of* $\{\widehat{Y}(t), \kappa(t)\}$*, and is given by*

$$\lim_{\varepsilon\to 0} \boldsymbol{\pi}_\varepsilon(x)(\mathbf{1}\otimes I) = 2\boldsymbol{\zeta}_1 e^{K_0 x}\Theta^{-1}, \tag{28}$$

$$\lim_{\varepsilon\to 0} \boldsymbol{F}_\varepsilon(0)(\mathbf{1}\otimes I) = \mathbf{0}, \tag{29}$$

where

$$\boldsymbol{\zeta}_1\Psi_1 = \mathbf{0}, \tag{30}$$

$$2\boldsymbol{\zeta}_1(-K_0)^{-1}\Theta^{-1}\mathbf{1} = 1. \tag{31}$$

PROOF. The solution of (18) is of the form $\boldsymbol{\zeta}_\varepsilon = \boldsymbol{\zeta}_0 + \varepsilon\boldsymbol{\zeta}_1 + o(\varepsilon)$ ([24, Theorem 5.4]) and (19) becomes

$$\begin{aligned}&\{\boldsymbol{\zeta}_0 + \varepsilon\boldsymbol{\zeta}_1 + o(\varepsilon)\}\mathbf{1} \\ &+ \{\boldsymbol{\zeta}_0 + \varepsilon\boldsymbol{\zeta}_1 + o(\varepsilon)\}(1/\varepsilon)(-K_\varepsilon)^{-1}\{(\varepsilon D + \Theta)^{-1} + \Psi_\varepsilon(\Theta - \varepsilon D)^{-1}\}\mathbf{1} = 1.\end{aligned} \tag{32}$$

We equate the coefficients of $1/\varepsilon$ on both sides of (32), use (20, 25) and find

$$-2\boldsymbol{\zeta}_0 K_0^{-1}\Theta^{-1}\mathbf{1} = 0.$$

Equation (15) implies that $\boldsymbol{\zeta}_\varepsilon \geq \mathbf{0}$ and, by continuity, $\boldsymbol{\zeta}_0 \geq \mathbf{0}$. Furthermore, Θ^{-1} is a diagonal matrix with strictly positive diagonal. Finally, K_0 has non-negative off-diagonal elements and is irreducible, so that $e^{K_0 u}$ is strictly positive for all $u > 0$, by Seneta [31, Theorem 2.7]. Moreover, the eigenvalues of K_0 have strictly negative real part by Lemma 3.6, so that $\int_0^\infty e^{K_0 u}\,\mathrm{d}u$ converges to $-K_0^{-1} > 0$. This implies that $\boldsymbol{\zeta}_0 = \mathbf{0}$, which proves (29). Using $\boldsymbol{\zeta}_0 = \mathbf{0}$, and equating coefficients of ε on both sides of (18) gives (30), while equating the coefficients of ε^0 on both sides of (32) leads to (31).

Gathering everything together, we obtain from (16)

$$\boldsymbol{\pi}_\varepsilon(x) = (1/\varepsilon)\{\varepsilon\boldsymbol{\zeta}_1 + o(\varepsilon)\}e^{K_\varepsilon x}\left[(\varepsilon D + \Theta)^{-1} \quad \Psi_\varepsilon(\Theta - \varepsilon D)^{-1}\right], \tag{33}$$

and (28) follows. Equation (29) is a direct consequence of (15).

To verify that the limiting distribution in Theorem 3.7 is the stationary density vector $\boldsymbol{g}(x)$ of the Markov-modulated Brownian motion, we use Asmussen [5]: by Theorem 2.1 and Corollary 4.1 there,

$$\boldsymbol{g}(x) = [e^{\Lambda x}(-\Lambda\mathbf{1})]^{\mathrm{T}}\Delta_{\boldsymbol{\alpha}}, \tag{34}$$

where $\boldsymbol{\alpha}$ is the stationary distribution vector of Q, $\Delta_{\boldsymbol{\alpha}} = \mathrm{diag}(\boldsymbol{\alpha})$, and Λ is a defective generator matrix satisfying

$$(1/2)V\Lambda^2 - D\Lambda + \Delta_{1/\boldsymbol{\alpha}}Q^{\mathrm{T}}\Delta_{\boldsymbol{\alpha}} = 0. \tag{35}$$

Define $Z = \Delta_{1/\boldsymbol{\alpha}}\Lambda^{\mathrm{T}}\Delta_{\boldsymbol{\alpha}}$ and rewrite (34) as

$$\boldsymbol{g}(x) = -\mathbf{1}^{\mathrm{T}}\Delta_{\boldsymbol{\alpha}}Z\Delta_{1/\boldsymbol{\alpha}}e^{\Delta_{\boldsymbol{\alpha}}Z\Delta_{1/\boldsymbol{\alpha}}x}\Delta_{\boldsymbol{\alpha}} = -\boldsymbol{\alpha}Ze^{Zx}. \tag{36}$$

The matrix $\Theta^{-1}Z\Theta$ is similar to Z and so to Λ^{T}, and so its eigenvalues all have strictly negative real parts. Furthermore, we find by (35) that

$$(1/2)Z^2V - ZD + Q = 0$$

and that $-\Theta^{-1}Z\Theta$ is a solution of (27). Therefore,

$$K_0 = \Theta^{-1}Z\Theta. \tag{37}$$

Substituting (37) into (28) gives $\lim_{\varepsilon\to 0}\boldsymbol{\pi}_\varepsilon(\mathbf{1}\otimes I) = 2\boldsymbol{\zeta}_1\Theta^{-1}e^{Zx}$. Finally, it is straightforward to verify that $\boldsymbol{\zeta}_1 = -\boldsymbol{\alpha}(\Theta^{-1}D + (1/2)\Theta\Psi_1\Theta^{-1})$, and consequently

$$\lim_{\varepsilon\to 0}\boldsymbol{\pi}_\varepsilon(\mathbf{1}\otimes I) = \boldsymbol{g}(x). \tag{38}$$

$\square$

REMARK 3.8. An alternative way to show that the stationary distribution of the approximating fluid process $\{\widehat{L}_\lambda(t), \widehat{\varphi}_\lambda(t)\}$ converges, as $\lambda \to \infty$, to the stationary distribution of the limiting Markov-modulated Brownian motion $\{\widehat{Y}(t), \kappa(t)\}$ is via the maximum representation of the relevant processes. Asmussen [5] derives the stationary distribution, both for fluid queues and for the MMBM in this manner, linking these to the distribution of the maximum of the time-reversed process. Following the arguments in Enikeeva *et al.* [18] and in Stenflo [32], one might show that there is continuity of the maximum distributions of the backward processes, as $\lambda \to \infty$, and consequently obtain the continuity of stationary distributions.

This would lead to a time reversal-based proof of convergence. As stated in the introduction, we aim at following the forward-time approach and so obtain a different representation of the stationary distribution. In addition, we obtain limiting properties for key matrices, and these results will be proved useful in future work.

4. Computational procedure. Theorem 3.7 indicates that the matrix Ψ_1 is the central ingredient in evaluating the stationary distribution of the Markov-modulated Brownian motion $\{\widehat{Y}(t), \varphi(t)\}$. We describe here how to use the splitting property (23) in numerically solving for Ψ_1 and Ψ_1^*.

Bini and Gemignani [9] consider quadratic matrix equations $C + AX + BX^2 = 0$ where the roots of the associated polynomial $\det(C + zA + z^2B)$ are split by a circle in $\mathbb{C}$, half being inside the disk and half outside. The problem in [9] is to find the minimal solution, that is, the solution matrix with all eigenvalues inside the disk.

In our case, the roots are split between the negative and the positive half-planes and we need to apply some transformation, such as the one described in Bini *et al.* [12] and based on the inverse Möbius mapping [4, Chapter 2.1]

$$w(z) = \frac{z-1}{z+1}. \tag{39}$$

This inverse mapping applies the open unit disk $|z| < 1$ onto the negative half-plane $\mathbb{C}_-$, the unit circle $|z| = 1$ minus the point $z = -1$ onto the imaginary axis $\mathbb{C}_0$, the outside $|z| > 1$ of the closed unit disk onto the positive half-plane $\mathbb{C}_+$, and the imaginary axis $\mathbb{C}_0$ onto the unit circle $|w| = 1$ minus the point $w = 1$.

Now, define $W(Z) = (Z - I)(Z + I)^{-1}$. Instead of solving $P(X) = X^2 + 2V^{-1}DX + 2V^{-1}Q = 0$ for $\Theta^{-1}\Psi_1$, we solve $H(Z) = 0$, where

$$\begin{aligned} H(Z) &= P(W(Z))(I + Z)^2 \\ &= P((Z - I)(Z + I)^{-1})(I + Z)^2 \end{aligned}$$

$$= (I + 2V^{-1}D + 2V^{-1}Q)Z^2 - 2(I - 2V^{-1}Q)Z + I \\ - 2V^{-1}D + 2V^{-1}Q.$$

The roots of $\det(H(z))$ are given by $\omega_i = w^{-1}(\theta_i) = (1 + \theta_i)/(1 - \theta_i)$ for $i = 1, \dots, 2m$, where the θ_is are defined in Lemma 3.4, and they satisfy the splitting property

$$0 \le |\omega_1|, \dots, |\omega_{m-1}| < \omega_m = 1 < |\omega_{m+1}|, \dots, |\omega_{2m}|. \tag{40}$$

We note that Bini and Gemignani [9] requires $|\omega_i| > 0$ for all i, but as seen in [13, Section 8.3], the weak inequality suffices.

Define Z_0 as the solution of $H(Z) = 0$ such that $\mathrm{sp}(Z_0) \le 1$. The matrix $W(Z_0) = (Z_0 - I)(Z_0 + I)^{-1}$ is a solution of $P(X) = 0$ with all eigenvalues in $\{\mathrm{Re}(z) \le 0\}$, and so $\Theta^{-1}\Psi_1 = (Z_0 - I)(Z_0 + I)^{-1}$.

Several iterative algorithms to compute Z_0 are discussed in [9]. Some have superlinear convergence, such as Cyclic reduction [10], Logarithmic reduction [25, Chapter 8], subspace iteration [3] or Graeffe iteration [10]. This means that the approximation error at the ith iteration is $O(\sigma^{2^i})$ with $\sigma = 1/|\omega_{m+1}| < 1$. These algorithms are globally convergent but they are not self-correcting. Since the coefficient matrices in $P(X)$ are of mixed signs, one might prefer the algorithm developed in [9]: it is self-correcting and the approximation error is $O(\sigma^{i2^k})$ for arbitrary k, which makes it arbitrarily fast.

As for Ψ_1^*, if we define Z_1 as the root of $H(Z)$ such that all of its eigenvalues are outside the closed unit disk, then $W(Z_1)$ has all its eigenvalues in the half-plane $\mathbb{C}_+$, and $\Theta^{-1}\Psi_1^* = -W(Z_1)$. The algorithms in [9], however, do not seem to be well adapted to the computation of Z_1, and we suggest to use a different transformation, in order to bring the eigenvalues of $-\Theta^{-1}\Psi_1^*$ inside the unit disk. This transformation is based on Möbius' mapping [4, Chapter 2.1]

$$z(w) = \frac{1 + w}{1 - w}. \tag{41}$$

This mapping applies the open unit disk $|w| < 1$ onto the positive half-plane $\mathbb{C}_+$, the unit circle $|w| = 1$ minus the point $w = 1$ onto the imaginary axis $\mathbb{C}_0 = \{z : \mathrm{Re}(z) = 0\}$ and the outside $|w| > 1$ of the closed unit disk onto the negative half-plane $\mathbb{C}_-$, finally, it applies the imaginary axis $\mathbb{C}_0$ onto the unit circle $|z| = 1$ minus the point $z = -1$.

Now, define $Z(W) = (I + W)(I - W)^{-1}$. Instead of solving $H(Z) = 0$ we solve $Q(W) = 0$ for the matrix solution W_1 with eigenvalues inside the unit disk, where

$$\begin{aligned}Q(W) &= P(Z(W))(I-W)^2,\\ &= (I-2V^{-1}D+2V^{-1}Q)W^2+2(I-2V^{-1}Q)W\\ &\quad + I+2V^{-1}D+2V^{-1}Q,\end{aligned}$$

and so $\Theta^{-1}\Psi_1^* = -(I+W_1)(I-W_1)^{-1}$.

APPENDIX A: PROOF OF LEMMA 3.4

The proof goes in four main steps. The matrix Ψ_ε is the stochastic (or sub-stochastic) solution of the Riccati equation

$$(C_\varepsilon^+)^{-1}T_\varepsilon^{+-}+(C_\varepsilon^+)^{-1}T_\varepsilon^{++}\Psi_\varepsilon+\Psi_\varepsilon|C_\varepsilon^-|^{-1}T_\varepsilon^{--}+\Psi_\varepsilon|C_\varepsilon^-|^{-1}T_\varepsilon^{-+}\Psi_\varepsilon=0$$

(Rogers [30]). We rewrite that equation as

$$\begin{aligned}&(1/\varepsilon)(\varepsilon D+\Theta)^{-1}+(1/\varepsilon)(\varepsilon D+\Theta)^{-1}(\varepsilon^2Q-I)\Psi_\varepsilon\\ &\quad+(1/\varepsilon)\Psi_\varepsilon|\varepsilon D-\Theta|^{-1}(\varepsilon^2Q-I)+(1/\varepsilon)\Psi_\varepsilon|\varepsilon D-\Theta|^{-1}\Psi_\varepsilon=0\end{aligned}\tag{42}$$

Thus, Ψ_ε is a solution of $\mathcal{F}_\varepsilon(X)=0$, where

$$\begin{aligned}\mathcal{F}_\varepsilon(X) &= (\varepsilon D+\Theta)^{-1}+(\varepsilon D+\Theta)^{-1}(\varepsilon^2Q-I)X\\ &\quad + X|\varepsilon D-\Theta|^{-1}(\varepsilon^2Q-I)+X|\varepsilon D-\Theta|^{-1}X.\end{aligned}$$

For $\varepsilon=0$, we see that $\mathcal{F}_0(I)=0$. It is tempting to invoke the Implicit Function Theorem and claim that Ψ_ε is an analytic function of ε in a neighborhood of $\varepsilon=0$. Unfortunately, the operator $\partial/\partial X\mathcal{F}_\varepsilon(X)$ is singular at the point $(\varepsilon=0, X=I)$, the Implicit Function Theorem does not apply, and we follow a longer, more tortuous path.

PROPOSITION A.1. *For $\varepsilon\ge 0$,*

$$\Psi_\varepsilon = I+\Phi_\varepsilon \quad \textit{where } \lim_{\varepsilon\to 0}\Phi_\varepsilon=0,\tag{43}$$

$$\Psi_\varepsilon^* = I+\Phi_\varepsilon^* \quad \textit{where } \lim_{\varepsilon\to 0}\Phi_\varepsilon^*=0.\tag{44}$$

PROOF. We note that

$$\begin{aligned}(\varepsilon D+\Theta)^{-1} &= \{I-\varepsilon\Theta^{-1}(-D)\}^{-1}\Theta^{-1}\\ &= \{I-\varepsilon\Theta^{-1}D+\varepsilon^2(\Theta^{-1}D)^2+O(\varepsilon^3)\}\Theta^{-1}\\ &= \Theta^{-1}-\varepsilon V^{-1}D+\varepsilon^2\Theta^{-1}V^{-1}D^2+O(\varepsilon^3),\end{aligned}\tag{45}$$

and similarly

$$|\varepsilon D - \Theta|^{-1} = \Theta^{-1} + \varepsilon V^{-1} D + \varepsilon^2 \Theta^{-1} V^{-1} D^2 + O(\varepsilon^3), \tag{46}$$

for ε sufficiently small. Thus, (42) implies that

$$\begin{aligned} &(1/\varepsilon)\{\Theta^{-1} - \varepsilon V^{-1} D + O(\varepsilon^2)\}(I + \varepsilon^2 Q \Psi_\varepsilon - \Psi_\varepsilon) \\ &\quad + (1/\varepsilon)\Psi_\varepsilon\{\Theta^{-1} + \varepsilon V^{-1} D + O(\varepsilon^2)\}(\varepsilon^2 Q - I + \Psi_\varepsilon) = 0, \end{aligned} \tag{47}$$

which can be reorganized as $\mathcal{G}(\varepsilon) + \mathcal{H}(\varepsilon) = 0$, where

$$\mathcal{G}(\varepsilon) = (1/\varepsilon)(\Theta^{-1} - \Theta^{-1}\Psi_\varepsilon - \Psi_\varepsilon\Theta^{-1} + \Psi_\varepsilon\Theta^{-1}\Psi_\varepsilon) \tag{48}$$

and

$$\begin{aligned} \mathcal{H}(\varepsilon) = (1/\varepsilon)\{&\varepsilon^2\Theta^{-1} Q \Psi_\varepsilon + (-\varepsilon V^{-1} D + O(\varepsilon^2))(I + \varepsilon^2 Q\Psi_\varepsilon - \Psi_\varepsilon) \\ &+ \varepsilon^2 \Psi_\varepsilon \Theta^{-1} Q + \Psi_\varepsilon(\varepsilon V^{-1} D + O(\varepsilon^2))(\varepsilon^2 Q - I + \Psi_\varepsilon)\}. \end{aligned} \tag{49}$$

The matrix $\mathcal{H}(\varepsilon)$ is bounded and therefore $\mathcal{G}(\varepsilon)$ too remains bounded as $\varepsilon \to 0$.

Now, we observe that Ψ_ε belongs to the compact set $\{M : M \geq 0, M\mathbf{1} \leq \mathbf{1}\}$ of (sub)stochastic matrices; therefore, for every sequence $\{\Psi_\varepsilon\}_{\varepsilon\to 0}$ there exist subsequences that converge. Let $\bar{\Psi}$ be the limit of one such convergent subsequence, and $\{\varepsilon_i\}_{i=1,2,\ldots}$ be a sequence such that $\varepsilon_i \to 0$ and $\Psi_{\varepsilon_i} \to \bar{\Psi}$ as $i \to \infty$. Since $\mathcal{G}(\varepsilon_i)$ remains bounded as $i \to \infty$, necessarily

$$\begin{aligned} \lim_{i\to\infty}(\Theta^{-1} - \Theta^{-1}\Psi_{\varepsilon_i} - \Psi_{\varepsilon_i}\Theta^{-1} + \Psi_{\varepsilon_i}\Theta^{-1}\Psi_{\varepsilon_i}) &= \lim_{i\to\infty}(I - \Psi_{\varepsilon_i})\Theta^{-1}(I - \Psi_{\varepsilon_i}) \\ &= (I - \bar{\Psi})\Theta^{-1}(I - \bar{\Psi}) \\ &= 0, \end{aligned}$$

and thus $\bar{\Psi} = I$. This follows from the facts that $\Theta^{-1}(I - \bar{\Psi})$ is a nilpotent matrix, that the trace of every nilpotent matrix is zero, and that $\bar{\Psi}$ is a (sub)stochastic matrix while Θ^{-1} is a strictly positive diagonal matrix.

All convergent subsequences having the same limit, the conclusion is that Ψ_ε converges to I as $\varepsilon \to 0$, and (43) follows. The proof of (44) is by analogous arguments. □

Proposition A.2. *For $\varepsilon > 0$, the matrices Φ_ε and Φ^*_ε are irreducible with non-negative off-diagonal elements, strictly negative diagonal elements, $\Phi_\varepsilon\mathbf{1} \leq \mathbf{0}$ and $\Phi^*_\varepsilon\mathbf{1} \leq \mathbf{0}$. In addition, under Assumption 3.1, $\Phi_\varepsilon\mathbf{1} = \mathbf{0}$ and $\Phi^*_\varepsilon\mathbf{1} < \mathbf{0}$.*

In short, Φ_ε is an irreducible generator and Φ^*_ε is an irreducible subgenerator.

PROOF. As we assume that the fluid queue is irreducible, Ψ_ε is an irreducible (sub)stochastic matrix for all $\varepsilon \geq 0$. Thus, we conclude from (43) that Φ_ε is irreducible and that its off-diagonal elements are non-negative. Furthermore, since $\Psi_\varepsilon \mathbf{1} \leq \mathbf{1}$, this implies that $\Phi_\varepsilon \mathbf{1} \leq \mathbf{0}$, so that its diagonal elements are strictly negative and Φ_ε is a (sub)generator. The same argument holds for Φ^*_ε.

Under Assumption 3.1, the matrix Ψ_ε is stochastic and the matrix Ψ^*_ε is strictly substochastic, and the last claim follows. □

PROPOSITION A.3. *The matrices* $(1/\varepsilon)\Phi_\varepsilon$ *and* $(1/\varepsilon)\Phi^*_\varepsilon$ *are bounded. Denoting by* $\bar{\Psi}_1$ *and* $\bar{\Psi}^*_1$ *the limits of any converging subsequences of* $(1/\varepsilon)\Phi_\varepsilon$ *and* $(1/\varepsilon)\Phi^*_\varepsilon$ *respectively, both* $\bar{\Psi}_1$ *and* $-\bar{\Psi}^*_1$ *are solutions of the equation*

$$(\Theta^{-1}Y)^2 + 2V^{-1}D\Theta^{-1}Y + 2V^{-1}Q = 0, \tag{50}$$

and are irreducible.

PROOF. Substituting (43) into (48, 49) gives us

$$\begin{aligned}
\mathcal{G}(\varepsilon) &= (1/\varepsilon)\{\Phi_\varepsilon\Theta^{-1}\Phi_\varepsilon\}\\
\mathcal{H}(\varepsilon) &= \varepsilon\Theta^{-1}Q(I+\Phi_\varepsilon) + [-V^{-1}D + O(\varepsilon)](\varepsilon^2 Q + \varepsilon^2 Q\Phi_\varepsilon - \Phi_\varepsilon)\\
&\quad + \varepsilon(I+\Phi_\varepsilon)\Theta^{-1}Q + (I+\Phi_\varepsilon)[V^{-1}D + O(\varepsilon)](\varepsilon^2 Q + \Phi_\varepsilon).
\end{aligned}$$

Clearly, $\lim_{\varepsilon\to 0}\mathcal{H}(\varepsilon) = 0$ and this implies that $\lim_{\varepsilon\to 0}(1/\varepsilon)\{\Phi_\varepsilon\Theta^{-1}\Phi_\varepsilon\} = 0$ since $\mathcal{G}(\varepsilon) + \mathcal{H}(\varepsilon) = 0$. Divide both sides of that equation by ε and obtain

$$(1/\varepsilon)^2\Phi_\varepsilon\Theta^{-1}\Phi_\varepsilon + 2\Theta^{-1}Q + \mathcal{R}(\varepsilon) = 0 \tag{51}$$

where

$$\begin{aligned}
\mathcal{R}(\varepsilon) &= \Theta^{-1}Q\Phi_\varepsilon + [-V^{-1}D + O(\varepsilon)](\varepsilon Q + \varepsilon Q\Phi_\varepsilon - (1/\varepsilon)\Phi_\varepsilon)\\
&\quad + \Phi_\varepsilon\Theta^{-1}Q + (I+\Phi_\varepsilon)[V^{-1}D + O(\varepsilon)]\{\varepsilon Q + (1/\varepsilon)\Phi_\varepsilon\}.
\end{aligned} \tag{52}$$

Now, there are three possible cases.

Case 1. $(1/\varepsilon)\Phi_\varepsilon \to 0$ as $\varepsilon \to 0$. Then, $\mathcal{R}(\varepsilon) \to 0$ and taking the limit of both sides of (51) as $\varepsilon \to 0$ leads to $2V^{-1}Q = 0$, which is not true.

Case 2. $(1/\varepsilon)\Phi_\varepsilon$ is unbounded in any neighborhood of $\varepsilon = 0$. Then, there exists a sequence $\{\varepsilon_k\}_{k=1,2\ldots}$ such that $\varepsilon_k \to 0$ and $\max_{ij}|\Phi_{\varepsilon_k}|_{ij}/\varepsilon_k \to \infty$. In this case, we may write $(1/\varepsilon)\Phi_\varepsilon = u_\varepsilon B_\varepsilon$, where u_ε is a scalar function such that $\lim_{k\to\infty} u_{\varepsilon_k} = \infty$ while B_{ε_k} remains bounded and does not converge to zero: since Φ_ε is an irreducible generator, its element of maximum absolute value is on the diagonal and we take $u_\varepsilon = \max_j |\Phi_\varepsilon|_{jj}/\varepsilon$, then B_ε is an irreducible generator with at least one diagonal element equal to -1, and with $|B_{ij}| \le 1$ for all i and j.

Next, for ε in the sequence $\{\varepsilon_k\}$, we replace $(1/\varepsilon)\Phi_\varepsilon$ in (51) by $u_\varepsilon B_\varepsilon$ and divide both sides of the equation by u_ε^2 to obtain

$$\begin{aligned} &B_\varepsilon\Theta^{-1}B_\varepsilon + (2/u_\varepsilon^2)\Theta^{-1}Q + (\varepsilon/u_\varepsilon)\Theta^{-1}QB_\varepsilon \\ &\qquad + [-V^{-1}D + O(\varepsilon)](\varepsilon/u_\varepsilon^2 Q + \varepsilon^2/u_\varepsilon QB_\varepsilon - (1/u_\varepsilon)B_\varepsilon) \\ &\qquad + ((1/u_\varepsilon)I + \varepsilon B_\varepsilon)[V^{-1}D + O(\varepsilon)]((\varepsilon/u_\varepsilon)Q + B_\varepsilon) = 0, \end{aligned} \tag{53}$$

This implies that

$$\lim_{k\to\infty} B_{\varepsilon_k}\Theta^{-1}B_{\varepsilon_k} = 0, \tag{54}$$

Now, take any converging subsequence of B_ε and denote its limit as B. By construction, the trace of $\Theta^{-1}B_\varepsilon$ is at most equal to $\min_j(-\sigma_j^{-1}) < 0$, independently of ε. Thus, the trace of $\Theta^{-1}B$ is strictly negative, the matrix $\Theta^{-1}B$ is not nilpotent, and $\Theta^{-1}B\Theta^{-1}B \neq 0$, which contradicts (54).

Case 3. $(1/\varepsilon)\Phi_\varepsilon$ is bounded and does not converge to 0. Then, from (52)

$$\mathcal{R}(\varepsilon) = (1/\varepsilon)2V^{-1}D\Phi_\varepsilon + \mathcal{R}^*(\varepsilon)$$

where $\mathcal{R}^*(\varepsilon)$ goes to 0 as ε goes to zero. This allows us to rewrite (51) as

$$(1/\varepsilon^2)\Phi_\varepsilon\Theta^{-1}\Phi_\varepsilon + 2\Theta^{-1}Q + (1/\varepsilon)2V^{-1}D\Phi_\varepsilon + \mathcal{R}^*(\varepsilon) = 0$$

and to conclude that

$$\lim_{\varepsilon\to 0}\{(1/\varepsilon^2)\Phi_\varepsilon\Theta^{-1}\Phi_\varepsilon + 2\Theta^{-1}Q + (1/\varepsilon)2V^{-1}D\Phi_\varepsilon + \mathcal{R}^*(\varepsilon)\} = 0. \tag{55}$$

Since $(1/\varepsilon)\Phi_\varepsilon$ is bounded, there exist subsequences $\{\varepsilon_k\}_{k=1,2,\ldots}$ such that $\varepsilon_k \to 0$ and such that $(1/\varepsilon_k)\Phi_{\varepsilon_k} \to \bar{\Psi}_1$. We take in (55) the limit along such a subsequence and conclude that $\bar{\Psi}_1$ is a solution of (50). The same approach is followed for Φ_ε^*.

Now, assume that $\bar{\Psi}_1$ is reducible. We may write

$$\Theta^{-1}\bar{\Psi}_1 = \begin{bmatrix} M_A & 0 \\ M_{AB} & M_B \end{bmatrix},$$

possibly after a permutation of rows and columns, where M_A and M_B are square matrices. As $\bar{\Psi}_1$ is a solution of (50), we are led to conclude that

$$Q = \begin{bmatrix} Q_A & 0 \\ Q_{AB} & Q_B \end{bmatrix}$$

which contradicts our assumption that Q is irreducible. Thus, $\bar{\Psi}_1$ is irreducible, and so is $\bar{\Psi}_1^*$ by the same argument. □

PROPOSITION A.4. *Consider the matrix equation*

$$VX^2 + 2DX + 2Q = 0 \tag{56}$$

and its associated matrix polynomial $\Gamma(z) = Vz^2 + 2Dz + 2Q$.

Under Assumption 3.1, $\det \Gamma(z)$ *has one root equal to zero,* $m-1$ *roots with strictly negative real parts, and* m *roots with strictly positive real parts.*

PROOF. Take $\{\varepsilon_k\}_{k=1,2,\ldots}$ to be a subsequence such that $\varepsilon_k \to 0$ and $(1/\varepsilon_k)\Phi_{\varepsilon_k} \to \bar{\Psi}_1$. By Proposition A.3, $\Theta^{-1}\bar{\Psi}_1$ is an irreducible generator and a solution of (56), and we write

$$\begin{aligned}\Gamma(z) &= z^2 V + 2Dz + 2Q - V((\Theta^{-1}\bar{\Psi}_1)^2 + 2V^{-1}D\Theta^{-1}\bar{\Psi}_1 + 2V^{-1}Q) \\ &= (Vz + V\Theta^{-1}\bar{\Psi}_1 + 2D)(zI - \Theta^{-1}\bar{\Psi}_1).\end{aligned} \tag{57}$$

We conclude that all eigenvalues of $\Theta^{-1}\bar{\Psi}_1$ are roots of $\det \Gamma(z)$. As we assume that the fluid queue is positive recurrent, $\Phi_\varepsilon \mathbf{1} = \mathbf{0}$ for all ε by Proposition A.2 and so $\Theta^{-1}\bar{\Psi}_1\mathbf{1} = \mathbf{0}$. Hence, $\det\Gamma(z)$ has at least one root equal to zero, and at least $m-1$ roots with strictly negative real parts.

We take a subsequence $\{\varepsilon_k^*\}_{k=1,2,\ldots}$ such that $\varepsilon_k^* \to 0$ and $(1/\varepsilon_k^*)\Phi^*_{\varepsilon_k^*} \to \bar{\Psi}_1^*$, and we assume in the remainder of the proof that ε belongs to such a sequence. In a similar manner as above, we show that

$$\Gamma(z) = (Vz - V\Theta^{-1}\bar{\Psi}_1^* + 2D)(zI + \Theta^{-1}\bar{\Psi}_1^*) \tag{58}$$

and all eigenvalues of $-\Theta^{-1}\bar{\Psi}_1^*$ are roots of $\det\Gamma(z)$. Since $\bar{\Psi}_1^*\mathbf{1} \le \mathbf{0}$, this shows that $\det\Gamma(z)$ has at least m roots with strictly positive real part if $\bar{\Psi}_1^*\mathbf{1} \neq \mathbf{0}$. In that case, the proof is complete as the polynomial $\det\Gamma(z)$ has at most $2m$ roots. It remains for us to show that $\bar{\Psi}_1^*\mathbf{1}$ cannot be equal to zero under Assumption 3.1.

We rewrite (50) as

$$Y\Theta^{-1}Y + 2V^{-1}DY + 2\Theta^{-1}Q = 0 \tag{59}$$

and define

$$A = \begin{bmatrix} 2V^{-1}D & 2\Theta^{-1}Q \\ -\Theta^{-1} & 0 \end{bmatrix}.$$

By Bini *et al.* [11, Theorem 2.1], $-\bar{\Psi}_1^*$ is a solution of (59) if and only if

$$A\begin{bmatrix} I & -\bar{\Psi}_1^* \\ 0 & I \end{bmatrix} = \begin{bmatrix} I & -\bar{\Psi}_1^* \\ 0 & I \end{bmatrix}\begin{bmatrix} 2V^{-1}D - \bar{\Psi}_1^*\Theta^{-1} & 0 \\ -\Theta^{-1} & \Theta^{-1}\bar{\Psi}_1^* \end{bmatrix},$$

and

$$\rho(A) = \rho(2V^{-1}D - \bar{\Psi}_1^*\Theta^{-1}) \cup \rho(\Theta^{-1}\bar{\Psi}_1^*), \tag{60}$$

where $\rho(\cdot)$ represents the spectrum of a matrix.

It is easy to verify that $A\boldsymbol{v} = \mathbf{0}$, where $\boldsymbol{v} = \left[\begin{smallmatrix}\boldsymbol{v}_1\\ \boldsymbol{v}_2\end{smallmatrix}\right]$, if and only if $\boldsymbol{v}_1 = \mathbf{0}$ and $Q\boldsymbol{v}_2 = \mathbf{0}$, that is, $\boldsymbol{v}_2$ is proportional to $\mathbf{1}$. Thus, A has only one eigenvector for the eigenvalue zero. In addition, the system $A\boldsymbol{w} = \boldsymbol{v}$ may be written as

$$\begin{aligned} 2V^{-1}D\boldsymbol{w}_1 + 2\Theta^{-1}Q\boldsymbol{w}_2 &= \mathbf{0},\\ -\Theta^{-1}\boldsymbol{w}_1 &= \mathbf{1} \end{aligned}$$

if we take $\boldsymbol{v}_2 = \mathbf{1}$, or

$$\begin{aligned} \boldsymbol{w}_1 &= -\Theta\mathbf{1},\\ Q\boldsymbol{w}_2 &= D\mathbf{1}, \end{aligned}$$

and the last equation does not have a solution under Assumption 3.1 as we show by premultiplying both sides by the stationary vector $\boldsymbol{\alpha}$ of Q. Thus, the spectrum $\rho(A)$ contains a single eigenvalue equal to zero.

Once we show that the matrix $2V^{-1}D - \bar{\Psi}_1^*\Theta^{-1}$ has one eigenvalue equal to zero, we conclude by (60) that $\Theta^{-1}\bar{\Psi}_1^*$ has no eigenvalue equal to zero and Proposition A.4 will be proved. We define

$$\begin{aligned} K_\varepsilon^* &= |C_\varepsilon^-|^{-1}T_\varepsilon^{--} + \Psi_\varepsilon^*(C_\varepsilon^+)^{-1}T_\varepsilon^{+-}\\ &= \frac{1}{\varepsilon}\{-|\Theta - \varepsilon D|^{-1}(I - \varepsilon^2 Q) + \Psi_\varepsilon^*(\Theta + \varepsilon D)^{-1}\}\\ &= \frac{1}{\varepsilon}\{-(\Theta^{-1} + \varepsilon V^{-1}D + O(\varepsilon^2))(I - \varepsilon^2 Q)\\ &\qquad + (I + \varepsilon\bar{\Psi}_1^* + o(\varepsilon))(\Theta^{-1} - \varepsilon V^{-1}D + O(\varepsilon^2))\} \end{aligned} \tag{61}$$

by (44, 45, 46) and the definition of $\bar{\Psi}_1^*$,

$$= \bar{\Psi}_1^*\Theta^{-1} - 2V^{-1}D + o(\varepsilon)/\varepsilon,$$

so that $\lim_{\varepsilon\to 0} K_\varepsilon^* = \bar{\Psi}_1^*\Theta^{-1} - 2V^{-1}D$.

By Govorun *et al.* [20, Theorem 4.2 and Lemma 4.4], $\rho(K_\varepsilon^*) = \rho(U_\varepsilon)$ where

$$U_\varepsilon = |C_\varepsilon^-|^{-1}T_\varepsilon^{--} + |C_\varepsilon^-|^{-1}T_\varepsilon^{-+}\Psi_\varepsilon$$

is a generator for all ε under Assumption 3.1. Thus, K_ε^* has one eigenvalue equal to zero for all ε and so has its limit as $\varepsilon \to 0$. This completes the proof. $\square$

Now we are ready to conclude. By the properties of the roots of $\det \Gamma(z)$ given in Proposition A.4, (22) has one unique solution suitable for the role of $\bar{\Psi}_1$ and another unique solution suitable for the role of $\bar{\Psi}_1^*$. Consequently, all convergent subsequences give the same limit Ψ_1 for $(1/\varepsilon_k)\Phi_{\varepsilon_k}$, and Ψ_1^* for $(1/\varepsilon_k)\Phi_{\varepsilon_k}^*$. □

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Guy Latouche
Université libre de Bruxelles
Département d'Informatique
E-mail: guy.latouche@ulb.ac.be

Giang Nguyen
The University of Adelaide
School of Mathematical Sciences
E-mail: giang.nguyen@adelaide.edu.au