Appendix

The incipient viscous flow of the cytosol can be assumed to be in the plane strain deformation state in the *r*-*θ* plane (Fig. 1b). The 2-D motion equations in the *r*-*θ* plane reduce to

$$\frac{\partial p}{\partial r} = \mu(\nabla^2 v_r - \frac{v_r}{r^2} - \frac{2}{r^2}\frac{\partial v_r}{\partial \theta}) \tag{23}$$

$$\frac{1}{r}\frac{\partial p}{\partial \theta} = \mu(\nabla^2 v_\theta - \frac{v_\theta}{r^2} + \frac{2}{r^2}\frac{\partial v_r}{\partial \theta}) \tag{24}$$

whereas the continuity equation takes the form

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r} + \frac{1}{r}\frac{\partial v_\theta}{\partial \theta} = 0 \tag{25}$$

By introducing a stream function ψ, that is,

$$v_r = \frac{1}{r}\frac{\partial \psi}{\partial \theta}, v_\theta = -\frac{1}{r}\frac{\partial \psi}{\partial r}, \tag{26}$$

Eqs. (23) and (24) lead to

$$\nabla^4 \psi = 0, \tag{27}$$

or

$$(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2})(\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \psi}{\partial \theta^2}) = 0. \tag{28}$$

Assuming the stream function in the form $\psi = g(r)\sin\theta\sin(kz)$, Eq. (28) reduces to

$$(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} - \frac{1}{r^2})(\frac{\partial^2 g(r)}{\partial r^2} + \frac{1}{r}\frac{\partial g(r)}{\partial r} - \frac{g(r)}{r^2}) = 0, \tag{29}$$

whose solution takes the form

$$g(r) = Ar^3 + Br + C\frac{1}{r} + Dr\ln r, \tag{30}$$

where A, B, C and D are coefficients to be determined.

Substituting Eq. (30) into Eq. (26), we have

$$v_r = -(Ar^2 + B + C\frac{1}{r^2} + D\ln r)\cos\theta\sin(kz), \tag{31}$$

$$v_\theta = -(3Ar^2 + B - C\frac{1}{r^2} + D\ln r + D)\sin\theta\sin(kz). \tag{32}$$

By substituting Eqs. (31) and (32) into the boundary conditions (i.e., Eqs. (6) and (7)), the coefficients A, B, C and D can be solved as

$$A = \frac{-v_0 q^2 \ln q}{(1-q^2)(1-q^2+(1+q^2)\ln q)}, \tag{33}$$

$$B = \frac{v_0 R_0{}^2(2\ln q + (1-q^2)(2\ln R_1 + 1))}{(1-q^2)(1-q^2+(1+q^2)\ln q)}, \tag{34}$$

$$C = \frac{v_0 R_0{}^2 R_1{}^2(q^2 - 1 - \ln q)}{q^2(1-q^2)(1-q^2+(1+q^2)\ln q)}, \tag{35}$$

$$D = \frac{-v_0 q^2}{(1-q^2)(1-q^2+(1+q^2)\ln q)}, \tag{36}$$

where $q = R_0 / R_1$.

The stress components of the cytosol at the microtubule/cytoplasm interface can be then obtained by substituting Eqs. (31)-(36) into Eq. (4),

$$\sigma_{rr} = -4\mu v_0 \cos\theta\sin(kz)\frac{(4q^4-2)\ln q + 3q^2 - q - 2}{R_0((q^4-1)\ln q - q^4 + 2q^2 - 1)} \tag{37}$$

$$\sigma_{r\theta} = 2\mu v_0 \sin\theta\sin(kz)\frac{-(3q^4+1)\ln q + q^4 - 1}{R_0((q^4-1)\ln q - q^4 + 2q^2 - 1)} \tag{38}$$

The surface traction of the cytosol along the interface can be obtained by integrating the stress field,

$$
\begin{aligned}
F_v &= \int_0^{2\pi} (\sigma_{rr} \cos\theta - \sigma_{r\theta} \sin\theta) R_0 d\theta \\
&= \mu v_0 \pi \sin(kz) \frac{(1-q^4)\ln q - 12q^2 + 2q^4 + 10}{(q^4-1)\ln q + 2q^2 - q^4 - 1} .
\end{aligned}
\tag{39}
$$