

# Note:Governing Euqations of General 3D duct flow

Email: jiaqi\_wang@sjtu.edu.cn

## I. Hard-walled cylindrical ducts as basis function

### A. Infinite straight duct mode

We began from the Helmholtz equation:

$$\nabla^2 \psi = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \psi}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 \psi}{\partial \theta^2} = -\alpha^2 \psi \quad (1)$$

Using separation of variables, Circular symmetry: modes have the from :  $\psi = F(r)G(\theta)$ ,

Then we have:

$$\begin{aligned} \left( \frac{\partial^2 F}{\partial r^2} + \frac{1}{r} \frac{\partial F}{\partial r} \right) G + \frac{F}{r^2} \frac{\partial^2 G}{\partial \theta^2} &= -\alpha^2 FG \\ \text{Then,} \\ \frac{\left( \frac{\partial^2 F}{\partial r^2} + \frac{1}{r} \frac{\partial F}{\partial r} \right)}{F} + \frac{1}{r^2} \frac{\frac{\partial^2 G}{\partial \theta^2}}{G} &= -\alpha^2 \end{aligned} \quad (2)$$

We assume that:

Due to periodicity, we require that  $\Phi$  satisfy,

$$\frac{d^2 G}{d\theta^2} = -m^2 G \rightarrow \Phi(\theta) = e^{\pm im\theta} \quad (3)$$

Thus, we have

$$F'' + \frac{1}{r} F' + \left( \alpha^2 - \frac{m^2}{r^2} \right) F = 0 \rightarrow F(r) = J_m(\alpha r) \quad (4)$$

Circular symmetry  $\psi = F(r)G(\theta)$ : modes explicitly given by:

$$\psi = J_m(\alpha_{m\mu} r) e^{\pm im\theta} \quad (5)$$

Hard walls:

$$J'_m(\alpha R) = 0 \rightarrow \alpha_{m\mu} = \frac{j'_{m\mu}}{R} \quad (6)$$

Soft walls without flow:

$$Z\alpha_{m\mu}J'_m(\alpha_{m\mu}R) = -iw\rho_0J_m(\alpha_{m\mu}R) \rightarrow \alpha_{m\mu}(Z) \quad (7)$$

Soft walls with flow:

$$Z\alpha_{m\mu}J'_m(\alpha_{m\mu}R) = (w - U_0\kappa_{m\mu})J_m(\alpha_{m\mu}R) \rightarrow \alpha_{m\mu}(Z) \quad (8)$$

A complete solution may be writtern as:

$$p(x, r, \theta) = \sum_{m=-\infty}^{\infty} \sum_{\mu=1}^{\infty} (A_{m\mu}e^{-i\kappa_{m\mu}x} + B_{m\mu}e^{i\kappa_{m\mu}x})U_{m\mu}(r)e^{im\theta} \quad (9)$$

In a hard-walled duct  $U_{m\mu}e^{-im\theta}$  are orthogonal. Normalise such that:

$$\int_0^{2\pi} \int_0^R U_{m\mu}(r)e^{-im\theta}U_{nv}(r)e^{-in\theta}rdr = 2\pi\delta_{\mu v}\delta_{mn} \quad (10)$$

Source expansion If  $p(0, t, \theta) = p_0(r, \theta)$  is source in hard-walled duct, then for  $x > 0$

$$\begin{aligned} p_0(r, \theta) &= \sum_{m=-\infty}^{\infty} \sum_{\mu=1}^{\infty} (A_{m\mu}e^{-i\kappa_{m\mu}0})U_{m\mu}(r)e^{-im\theta} \\ p_0(r, \theta)\underline{U_{nv}(r)e^{-in\theta}r} &= \sum_{m=-\infty}^{\infty} \sum_{\mu=1}^{\infty} (A_{m\mu}e^{-i\kappa_{m\mu}0})U_{m\mu}(r)e^{-im\theta}\underline{U_{nv}(r)e^{-in\theta}r} \\ \underline{\int_0^{2\pi} \int_0^R p_0(r, \theta)\underline{U_{nv}(r)e^{-in\theta}r}drd\theta} &= \underline{\int_0^{2\pi} \int_0^R \sum_{m=-\infty}^{\infty} \sum_{\mu=1}^{\infty} (A_{m\mu}e^{-i\kappa_{m\mu}0})U_{m\mu}(r)e^{-im\theta}\underline{U_{nv}(r)e^{-in\theta}r}drd\theta} \\ \underline{\int_0^{2\pi} \int_0^R p_0(r, \theta)\underline{U_{nv}(r)e^{-in\theta}r}drd\theta} &= \sum_{m=-\infty}^{\infty} \sum_{\mu=1}^{\infty} A_{m\mu} \underline{\int_0^{2\pi} \int_0^R U_{m\mu}(r)e^{-im\theta}\underline{U_{nv}(r)e^{-in\theta}r}drd\theta} \\ A_{nv} &= \frac{1}{2\pi} \underline{\int_0^{2\pi} \int_0^R p_0(r, \theta)\underline{U_{nv}(r)e^{-in\theta}r}drd\theta} \end{aligned} \quad (11)$$

and  $B_{nv} = 0$ . The same for  $x < 0$  with  $A_{nv}$  and  $B_{nv}$  interchanged.

A finite number of modes (cut-on modes) survive at large distances. Just 1 mode if  $kR \ll 1$ : only  $A_{01}$  important.

## B. General duct mode

The pressure and velocity can now be expressed as Fourier series. Upper indices shall be used to denote temporal decompositions:

$$\begin{aligned}
\hat{p} &= \sum_{a=-\infty}^{\infty} P^a(\mathbf{x})e^{-ia\omega t} \\
\hat{u} &= \sum_{a=-\infty}^{\infty} U^a(\mathbf{x})e^{-ia\omega t} \\
\hat{v} &= \sum_{a=-\infty}^{\infty} V^a(\mathbf{x})e^{-ia\omega t} \\
\hat{w} &= \sum_{a=-\infty}^{\infty} W^a(\mathbf{x})e^{-ia\omega t}
\end{aligned} \tag{12}$$

$$\begin{aligned}
P^a &= \sum_{\alpha=0}^{\infty} P_{\alpha m \mu}^a(s) \psi_{\alpha m \mu}(s, r, \theta) = \sum_{m=-\infty}^{\infty} \sum_{\mu=1}^{\infty} P_{\alpha m \mu}^a(s) \psi_{\alpha m \mu}(s, r, \theta) \\
U^a &= \sum_{\alpha=0}^{\infty} U_{\alpha m \mu}^a(s) \psi_{\alpha m \mu}(s, r, \theta) = \sum_{m=-\infty}^{\infty} \sum_{\mu=1}^{\infty} U_{\alpha m \mu}^a(s) \psi_{\alpha m \mu}(s, r, \theta) \\
V^a &= \sum_{\alpha=0}^{\infty} V_{\alpha m \mu}^a(s) \psi_{\alpha m \mu}(s, r, \theta) = \sum_{m=-\infty}^{\infty} \sum_{\mu=1}^{\infty} V_{\alpha m \mu}^a(s) \psi_{\alpha m \mu}(s, r, \theta) \\
W^a &= \sum_{\alpha=0}^{\infty} W_{\alpha m \mu}^a(s) \psi_{\alpha m \mu}(s, r, \theta) = \sum_{m=-\infty}^{\infty} \sum_{\mu=1}^{\infty} W_{\alpha m \mu}^a(s) \psi_{\alpha m \mu}(s, r, \theta)
\end{aligned} \tag{13}$$

A solution of  $\psi$  may have the form the same as the hard walls modes:

$$\psi_{m\mu}(r) = C_{\alpha m \mu} J_m\left(\frac{j'_{m\mu} r}{h}\right) e^{im\theta} \tag{14}$$

where should be normalized according to:

$$\int_0^{2\pi} \int_0^h \psi_{\alpha m \mu} \psi_{\beta n \nu} r dr d\theta = \delta_{\mu\nu} \delta_{mn} \tag{15}$$

### C. Normalised Modes $\rightarrow C_{\alpha m \mu}$

Relation involving integrals:

$$\begin{aligned}
& 2 \int \alpha^2 x J_m(\alpha x)^2 dx = (\alpha^2 x^2 - m^2) J_m(\alpha x)^2 + \alpha^2 x^2 J'_m(\alpha x)^2 \\
& \rightarrow 2 \int_0^h \alpha^2 x J_m(\alpha x)^2 dx = [(\alpha^2 x^2 - m^2) J_m(\alpha x)^2 + \alpha^2 x^2 J'_m(\alpha x)^2]_0^h \\
& = [(\alpha^2 x^2 - m^2) J_m(\alpha x)^2 + \alpha^2 x^2 J'_m(\alpha x)^2]_h - [(\alpha^2 x^2 - m^2) J_m(\alpha x)^2 + \alpha^2 x^2 J'_m(\alpha x)^2]_0 \\
& = [(\alpha^2 h^2 - m^2) J_m(\alpha h)^2 + \alpha^2 h^2 J'_m(\alpha h)^2] - [(\alpha^2 0^2 - m^2) J_m(\alpha 0)^2 + \alpha^2 0^2 J'_m(\alpha 0)^2] \\
& = (\alpha^2 h^2 - m^2) J_m(\alpha h)^2 + \alpha^2 h^2 J'_m(\alpha h)^2
\end{aligned} \tag{16}$$

With hard-walled boundary condition:

$$J'_m(\alpha h) = 0 \rightarrow \alpha_{m\mu} = \frac{j'_{m\mu}}{h} (\text{eigenvalues}) \tag{17}$$

Then, we have:

$$\begin{aligned}
& \int_0^h r J_m(\alpha r)^2 dr \\
&= \begin{cases} \frac{1}{2\alpha_{m\mu}^2} (\alpha_{m\mu}^2 h^2 - m^2) J_m(\alpha_{m\mu} h)^2, m \neq 0 \\ \frac{1}{2} (h^2) J_0(\alpha_{m\mu} h)^2, m = 0 \end{cases} \\
&= \begin{cases} \left( \frac{J_m(\alpha_{m\mu} h) \sqrt{(h^2 - \frac{m^2}{\alpha_{m\mu}^2})}}{\sqrt{2}} \right)^2, m \neq 0 \\ \frac{1}{2} (h^2) J_0(\alpha_{m\mu} h)^2, m = 0 \end{cases} \\
&= \begin{cases} \left( \frac{h^2}{2} \left( 1 - \frac{m^2}{j'^2_{m\mu}} \right) J_m^2(j'_{m\mu}) \right), m \neq 0 \\ \frac{1}{2} h^2 J_0^2(j'_{m\mu}), m = 0 \end{cases}
\end{aligned} \tag{18}$$

Thus,

$$C_{\alpha_{m\mu}} = \begin{cases} \frac{1}{\sqrt{\frac{\pi}{2} h^2 J_0^2(j'_{m\mu})}}, m = 0 \\ \frac{1}{\sqrt{\left( \frac{\pi h^2}{2} \left( 1 - \frac{m^2}{j'^2_{m\mu}} \right) J_m^2(j'_{m\mu}) \right)}}, m \neq 0 \end{cases} \tag{19}$$

#### D. Slowly varying ducts

waiting for updating.....

#### E. Orthogonal-eigenvector

ref:https:

[www.mathworks.com/help/matlab/ref/eigs.html](http://www.mathworks.com/help/matlab/ref/eigs.html)

Eigenvectors, returned as a matrix. The columns in V correspond to the eigenvalues along the diagonal of D. The form and normalization of V depends on the combination of input arguments:

[V,D] = eigs(A) returns matrix V, whose columns are the eigenvectors of A such that A\*V = V\*D. The eigenvectors in V are normalized so that the 2-norm of each is 1.

If A is symmetric, then the eigenvectors, V, are orthonormal.

[V,D] = eigs(A,B) returns V as a matrix whose columns are the generalized eigenvectors that satisfy A\*V = B\*V\*D. The 2-norm of each eigenvector is not necessarily 1.

If B is symmetric positive definite, then the eigenvectors in V are normalized so that the B-norm of each is 1. If A is also symmetric, then the eigenvectors are B-orthonormal.

We could further study this question!!

if we can use the GramSchmidt mode as basis??

## II. Mass equation

Mass consevation:

$$-iakP^a + \nabla \cdot \mathbf{U}^a = \sum_{b=-\infty}^{+\infty} (-P^{a-b} \nabla \cdot \mathbf{U}^b - \mathbf{U}^{a-b} \cdot \nabla P^b - \frac{B}{2A} iakP^b P^{a-b}) \quad (20)$$

First, derivation of eq1:

We know that:

$$h_s = 1 - \kappa r \cos(\phi), h_r = 1, h_\theta = r \quad (21)$$

Then,

$$\begin{aligned} \nabla \cdot \mathbf{U}^a &= \frac{1}{h_1 h_2 h_3} \left[ \frac{\partial(v_1 h_2 h_3)}{\partial w_1} + \frac{\partial(v_2 h_3 h_1)}{\partial w_2} + \frac{\partial(v_3 h_1 h_2)}{\partial w_3} \right] \\ &= \frac{1}{r(1 - \kappa r \cos(\phi))} \left[ \frac{\partial(U^a r)}{\partial s} + \frac{\partial(V^a r(1 - \kappa r \cos(\phi)))}{\partial r} + \frac{\partial(W^a(1 - \kappa r \cos(\phi)))}{\partial \theta} \right] \end{aligned} \quad (22)$$

Thus, we have the mass equation, approximate RHS by:

$$\begin{aligned} \nabla \cdot \mathbf{U}^b &= ib\kappa P^b + o(M^2) \\ \nabla P^b &= ib\kappa \mathbf{U}^b + o(M^2) \end{aligned} \quad (23)$$

Then we have

$$\begin{aligned} -iakP^a + \frac{1}{r(1 - \kappa r \cos(\phi))} \left[ \frac{\partial(U^a r)}{\partial s} + \frac{\partial(V^a r(1 - \kappa r \cos(\phi)))}{\partial r} + \frac{\partial(W^a(1 - \kappa r \cos(\phi)))}{\partial \theta} \right] \\ = \sum_{b=-\infty}^{+\infty} (-ib\kappa P^{a-b} P^b - ib\kappa U^{a-b} U^b - ib\kappa V^{a-b} V^b - ib\kappa W^{a-b} W^b - \frac{B}{2A} iakP^b P^{a-b}) \end{aligned} \quad (24)$$

The fourier harmonics are expanded as follows:

$$\begin{aligned} P^a &= \sum_{\beta=0}^{\infty} P_{\beta}^a(s) \psi_{\beta}(s, r, \theta) \\ U^a &= \sum_{\beta=0}^{\infty} U_{\beta}^a(s) \psi_{\beta}(s, r, \theta) \\ V^a &= \sum_{\beta=0}^{\infty} V_{\beta}^a(s) \psi_{\beta}(s, r, \theta) \\ W^a &= \sum_{\beta=0}^{\infty} W_{\beta}^a(s) \psi_{\beta}(s, r, \theta) \end{aligned} \quad (25)$$

with normalized relation:

$$\int_0^{2\pi} \int_0^h \psi_\alpha \psi_\beta r dr d\theta = \delta_{\alpha\beta} \quad (26)$$

Reorganize the eq5:

$$\begin{aligned} & -ia\kappa P^a(1 - \kappa r \cos(\phi)) + \frac{1}{r} \frac{\partial(U^a r)}{\partial s} + \frac{1}{r} \frac{\partial(V^a r(1 - \kappa r \cos(\phi)))}{\partial r} + \frac{1}{r} \frac{\partial(W^a(1 - \kappa r \cos(\phi)))}{\partial \theta} \\ & = (1 - \kappa r \cos(\phi)) \sum_{b=-\infty}^{+\infty} (-ib\kappa P^{a-b} P^b - ib\kappa U^{a-b} U^b - ib\kappa V^{a-b} V^b - ib\kappa W^{a-b} W^b - \frac{B}{2A} iak P^b P^{a-b}) \end{aligned} \quad (27)$$

Intergal and insert eq 6, 7 into eq 8:

1. the first term:

$$\begin{aligned} & \int_0^{2\pi} \int_0^h \psi_\alpha r [-ia\kappa(1 - \kappa r \cos(\phi)) P^a] dr d\theta \\ & = -ia\kappa \sum_{\beta} \int_0^{2\pi} \int_0^h \psi_\alpha \psi_\beta r [(1 - \kappa r \cos(\phi))] dr d\theta P_\beta^a \\ & = -ia\kappa \Psi_{\alpha\beta} [r(1 - \kappa \cos(\phi))] P_\beta^a \\ & \quad (summationconvention) \end{aligned} \quad (28)$$

2. the second term:

$$\begin{aligned} & \int_0^{2\pi} \int_0^h \psi_\alpha r \left[ \frac{1}{r} \frac{\partial(U^a r)}{\partial s} \right] dr d\theta \\ & = \int_0^{2\pi} \int_0^h \psi_\alpha r \frac{\partial(\psi_\beta U_\beta^a)}{\partial s} dr d\theta \\ & = \int_0^{2\pi} \int_0^h \psi_\alpha \psi_\beta r \frac{\partial(U_\beta^a)}{\partial s} dr d\theta + \int_0^{2\pi} \int_0^h \psi_\alpha r \frac{\partial(\psi_\beta)}{\partial s} dr d\theta U_\beta^a \\ & = \frac{dU_\beta^a}{ds} \int_0^{2\pi} \int_0^h \psi_\alpha \psi_\beta r dr d\theta + \int_0^{2\pi} \int_0^h r \frac{\partial(\psi_\alpha \psi_\beta)}{\partial s} dr d\theta U_\beta^a - \int_0^{2\pi} \int_0^h \psi_\beta r \frac{\partial(\psi_\alpha)}{\partial s} dr d\theta U_\beta^a \\ & = \frac{dU_\beta^a}{ds} \delta_{\alpha\beta} + \frac{\partial(\int_0^{2\pi} \int_0^h r \psi_\alpha \psi_\beta dr d\theta)}{\partial s} U_\beta^a - \int_0^{2\pi} \int_0^h \frac{\partial(\psi_\alpha)}{\partial s} \psi_\beta r dr d\theta U_\beta^a \\ & = \frac{dU_\alpha^a}{ds} + 0 - \Psi_{\{\alpha\}\beta} [r] U_\beta^a \end{aligned} \quad (29)$$

3. the third term:

$$\begin{aligned} & \int_0^{2\pi} \int_0^h \psi_\alpha r \left[ \frac{1}{r} \frac{\partial(V^a r(1 - \kappa r \cos(\phi)))}{\partial r} \right] dr d\theta \\ & = \int_0^{2\pi} \int_0^h \psi_\alpha \frac{\partial(\psi_\beta r(1 - \kappa r \cos(\phi)))}{\partial r} dr d\theta V_\beta^a \\ & = \int_0^{2\pi} \int_0^h \frac{\partial(\psi_\alpha \psi_\beta r(1 - \kappa r \cos(\phi)))}{\partial r} dr d\theta V_\beta^a - \int_0^{2\pi} \int_0^h \psi_\beta r(1 - \kappa r \cos(\phi)) \frac{\partial(\psi_\alpha)}{\partial r} dr d\theta V_\beta^a \\ & = 0(periodic) - \Psi_{[\alpha]\beta} [r(1 - \kappa r \cos(\phi))] V_\beta^a \end{aligned} \quad (30)$$

4. the fourth term:

$$\begin{aligned}
& \int_0^{2\pi} \int_0^h \psi_\alpha r \left[ \frac{1}{r} \frac{\partial(W^a(1 - \kappa r \cos(\phi)))}{\partial \theta} \right] dr d\theta \\
&= \int_0^{2\pi} \int_0^h \psi_\alpha \left[ \frac{\partial(\psi_\beta(1 - \kappa r \cos(\phi)))}{\partial \theta} \right] dr d\theta W_\beta^a \\
&= \int_0^{2\pi} \int_0^h \left[ \frac{\partial(\psi_\alpha \psi_\beta(1 - \kappa r \cos(\phi)))}{\partial \theta} \right] dr d\theta W_\beta^a - \int_0^{2\pi} \int_0^h \psi_\beta(1 - \kappa r \cos(\phi)) \left[ \frac{\partial(\psi_\alpha)}{\partial \theta} \right] dr d\theta W_\beta^a \quad (31) \\
&= \int_0^h [\psi_\alpha \psi_\beta(1 - \kappa r \cos(\phi))]_0^{2\pi} dr W_\beta^a - \int_0^{2\pi} \int_0^h \psi_\beta(1 - \kappa r \cos(\phi)) \left[ \frac{\partial(\psi_\alpha)}{\partial \theta} \right] dr d\theta W_\beta^a \\
&= 0 - \Psi_{(\alpha)\beta}[(1 - \kappa r \cos(\phi))] W_\beta^a
\end{aligned}$$

5. the RHS term:

$$\begin{aligned}
& \int_0^{2\pi} \int_0^h \psi_\alpha r [(1 - \kappa r \cos(\phi)) \sum_{b=-\infty}^{+\infty} (-ib\kappa P^{a-b} P^b - ib\kappa U^{a-b} U^b - ib\kappa V^{a-b} V^b - ib\kappa W^{a-b} W^b - \frac{B}{2A} ia\kappa P^b P^{a-b})] dr d\theta \\
&= \int_0^{2\pi} \int_0^h \psi_\alpha \psi_\beta \psi_\gamma r (1 - \kappa r \cos(\phi)) dr d\theta \\
& \quad \sum_{b=-\infty}^{+\infty} (-ib\kappa P_\beta^{a-b} P_\gamma^b - ib\kappa U_\beta^{a-b} U_\gamma^b - ib\kappa V_\beta^{a-b} V_\gamma^b - ib\kappa W_\beta^{a-b} W_\gamma^b - ia\kappa \frac{B}{2A} P_\beta^{a-b} P_\gamma^b) \\
&= \Psi_{\alpha\beta\gamma}[r(1 - \kappa r \cos(\phi))] \sum_{b=-\infty}^{+\infty} (-ib\kappa P_\beta^{a-b} P_\gamma^b - ib\kappa U_\beta^{a-b} U_\gamma^b - ib\kappa V_\beta^{a-b} V_\gamma^b - ib\kappa W_\beta^{a-b} W_\gamma^b - ia\kappa \frac{B}{2A} P_\beta^{a-b} P_\gamma^b) \quad (32)
\end{aligned}$$

Finally, we obtain the mass equation in the form of eigenfunction, the idea is same as Galerkin

method:

$$\begin{aligned}
& \frac{dU_\alpha^a}{ds} - \Psi_{\{\alpha\}\beta}[r] U_\beta^a - ia\kappa \Psi_{\alpha\beta}[r(1 - \kappa r \cos(\phi))] P_\beta^a - \Psi_{[\alpha]\beta}[r(1 - \kappa r \cos(\phi))] V_\beta^a - \Psi_{(\alpha)\beta}[(1 - \kappa r \cos(\phi))] W_\beta^a \\
&= \Psi_{\alpha\beta\gamma}[r(1 - \kappa r \cos(\phi))] \sum_{b=-\infty}^{+\infty} (-ib\kappa P_\beta^{a-b} P_\gamma^b - ib\kappa U_\beta^{a-b} U_\gamma^b - ib\kappa V_\beta^{a-b} V_\gamma^b - ib\kappa W_\beta^{a-b} W_\gamma^b - ia\kappa \frac{B}{2A} P_\beta^{a-b} P_\gamma^b) \quad (33)
\end{aligned}$$

### III. Momentum equation

Momentum consevation:

$$-ia\kappa \mathbf{U}^a + \nabla P^a = \sum_{b=-\infty}^{\infty} (-\mathbf{U}^{a-b} \cdot \nabla \mathbf{U}^b + P^{a-b} \nabla P^b) \quad (34)$$

First, we know that

$$\nabla P^a = \sum_i \frac{1}{h_i} \frac{\partial f}{\partial w_i} \hat{h}_i = \frac{1}{1 - \kappa r \cos \phi} \frac{\partial P^a}{\partial s} \hat{e}_s + \frac{\partial P^a}{\partial r} \hat{e}_r + \frac{1}{r} \frac{\partial P^a}{\partial \theta} \hat{e}_\theta \quad (35)$$

The RHS term is a bit complex, with the divergence of a vector  $\mathbf{U}$  with its gradient, with

First, we know that

$$(\mathbf{v} \cdot \nabla) \mathbf{v}^b = \begin{cases} term1 : \mathcal{D}v_1^b + \frac{v_2^b}{h_2 h_1} (v_1 \frac{\partial h_1}{\partial \xi_2} - v_2 \frac{\partial h_2}{\partial \xi_1}) + \frac{v_3^b}{h_3 h_1} (v_1 \frac{\partial h_1}{\partial \xi_3} - v_2 \frac{\partial h_3}{\partial \xi_1}) \\ term2 : \mathcal{D}v_2^b + \frac{v_3^b}{h_3 h_2} (v_2 \frac{\partial h_2}{\partial \xi_3} - v_3 \frac{\partial h_3}{\partial \xi_2}) + \frac{v_1^b}{h_1 h_2} (v_2 \frac{\partial h_2}{\partial \xi_1} - v_1 \frac{\partial h_1}{\partial \xi_2}) \\ term3 : \mathcal{D}v_3^b + \frac{v_1^b}{h_1 h_3} (v_3 \frac{\partial h_3}{\partial \xi_1} - v_1 \frac{\partial h_1}{\partial \xi_3}) + \frac{v_2^b}{h_2 h_3} (v_3 \frac{\partial h_3}{\partial \xi_2} - v_2 \frac{\partial h_2}{\partial \xi_3}) \end{cases} \quad (36)$$

Besides,

$$\mathcal{D} = \frac{v_1}{h_1} \frac{\partial}{\partial \xi_1} + \frac{v_2}{h_2} \frac{\partial}{\partial \xi_2} + \frac{v_3}{h_3} \frac{\partial}{\partial \xi_3} \quad (37)$$

Thus, we have:

$$\begin{aligned} & -\mathbf{U}^{a-b} \cdot \nabla \mathbf{U}^b = \\ & - \sum_{b=-\infty}^{\infty} \left\{ \begin{aligned} & term\mathcal{D}1 : \frac{U^{a-b}}{1-\kappa r \cos \phi} \frac{\partial U^b}{\partial s} + V^{a-b} \frac{\partial U^b}{\partial r} + \frac{W^{a-b}}{r} \frac{\partial U^b}{\partial \theta} \\ & term\mathcal{D}2 : \frac{U^{a-b}}{1-\kappa r \cos \phi} \frac{\partial V^b}{\partial s} + V^{a-b} \frac{\partial V^b}{\partial r} + \frac{W^{a-b}}{r} \frac{\partial V^b}{\partial \theta} \\ & term\mathcal{D}3 : \frac{U^{a-b}}{1-\kappa r \cos \phi} \frac{\partial W^b}{\partial s} + V^{a-b} \frac{\partial W^b}{\partial r} + \frac{W^{a-b}}{r} \frac{\partial W^b}{\partial \theta} \end{aligned} \right. \\ & - \sum_{b=-\infty}^{\infty} \left\{ \begin{aligned} & term\mathcal{X}1 : \frac{V^b}{1-\kappa r \cos \phi} (U^{a-b} \frac{\partial(1-\kappa r \cos \phi)}{\partial r} - V^{a-b} \frac{\partial 1}{\partial s}) + \frac{W^b}{r(1-\kappa r \cos \phi)} (U^{a-b} \frac{\partial(1-\kappa r \cos \phi)}{\partial \theta} - V^{a-b} \frac{\partial r}{\partial s}) \\ & term\mathcal{X}2 : \frac{W^b}{r} (V^{a-b} \frac{\partial 1}{\partial \theta} - W^{a-b} \frac{\partial r}{\partial r}) + \frac{U^b}{(1-\kappa r \cos \phi)1} (V^{a-b} \frac{\partial 1}{\partial s} - U^{a-b} \frac{\partial(1-\kappa r \cos \phi)}{\partial r}) \\ & term\mathcal{X}3 : \frac{U^b}{(1-\kappa r \cos \phi)r} (W^{a-b} \frac{\partial h_3}{\partial s} - U^{a-b} \frac{\partial(1-\kappa r \cos \phi)}{\partial \theta}) + \frac{V^b}{1h_3} (W^{a-b} \frac{\partial h_3}{\partial r} - V^{a-b} \frac{\partial 1}{\partial \theta}) \end{aligned} \right. = \\ & \sum_{b=-\infty}^{\infty} \left\{ \begin{aligned} & term\mathcal{D}1 : -\frac{U^{a-b}}{1-\kappa r \cos \phi} \frac{\partial U^b}{\partial s} - V^{a-b} \frac{\partial U^b}{\partial r} - \frac{W^{a-b}}{r} \frac{\partial U^b}{\partial \theta} \\ & term\mathcal{D}2 : -\frac{U^{a-b}}{1-\kappa r \cos \phi} \frac{\partial V^b}{\partial s} - V^{a-b} \frac{\partial V^b}{\partial r} - \frac{W^{a-b}}{r} \frac{\partial V^b}{\partial \theta} \\ & term\mathcal{D}3 : -\frac{U^{a-b}}{1-\kappa r \cos \phi} \frac{\partial W^b}{\partial s} - V^{a-b} \frac{\partial W^b}{\partial r} - \frac{W^{a-b}}{r} \frac{\partial W^b}{\partial \theta} \end{aligned} \right. \\ & + \sum_{b=-\infty}^{\infty} \left\{ \begin{aligned} & term\mathcal{X}1 : \frac{\kappa \cos \phi}{1-\kappa r \cos \phi} U^{a-b} V^b - \frac{\kappa \sin \phi}{(1-\kappa r \cos \phi)} U^{a-b} W^b \\ & term\mathcal{X}2 : \frac{W^{a-b} W^b}{r} - \frac{\kappa \cos \phi}{(1-\kappa r \cos \phi)} U^{a-b} U^b \\ & term\mathcal{X}3 : \frac{\kappa \sin \phi}{(1-\kappa r \cos \phi)} U^{a-b} U^b - \frac{W^{a-b} V^b}{r} \end{aligned} \right. \quad (38) \end{aligned}$$

Finally, we could derive the momentum conservation equation, with final term approximate by



eq 4:

$$\begin{aligned}
& \left\{ \begin{aligned} & -ia\kappa U^a + \frac{1}{1-\kappa r \cos \phi} \frac{\partial P^a}{\partial s} \\ & -ia\kappa V^a + \frac{\partial P^a}{\partial r} \\ & -ia\kappa W^a + \frac{1}{r} \frac{\partial P^a}{\partial \theta} \end{aligned} \right. \\
& = \sum_{b=-\infty}^{\infty} \left\{ \begin{aligned} & term\mathcal{D}1 : -\frac{U^{a-b}}{1-\kappa r \cos \phi} \frac{\partial U^b}{\partial s} - V^{a-b} \frac{\partial U^b}{\partial r} - \frac{W^{a-b}}{r} \frac{\partial U^b}{\partial \theta} \\ & term\mathcal{D}2 : -\frac{U^{a-b}}{1-\kappa r \cos \phi} \frac{\partial V^b}{\partial s} - V^{a-b} \frac{\partial V^b}{\partial r} - \frac{W^{a-b}}{r} \frac{\partial V^b}{\partial \theta} \\ & term\mathcal{D}3 : -\frac{U^{a-b}}{1-\kappa r \cos \phi} \frac{\partial W^b}{\partial s} - V^{a-b} \frac{\partial W^b}{\partial r} - \frac{W^{a-b}}{r} \frac{\partial W^b}{\partial \theta} \end{aligned} \right. \quad (39) \\
& + \sum_{b=-\infty}^{\infty} \left\{ \begin{aligned} & term\mathcal{X}1 : \frac{\kappa \cos \phi}{1-\kappa r \cos \phi} U^{a-b} V^b - \frac{\kappa \sin \phi}{(1-\kappa r \cos \phi)} U^{a-b} W^b \\ & term\mathcal{X}2 : \frac{W^{a-b} W^b}{r} - \frac{\kappa \cos \phi}{(1-\kappa r \cos \phi)} U^{a-b} U^b \\ & term\mathcal{X}3 : \frac{\kappa \sin \phi}{(1-\kappa r \cos \phi)} U^{a-b} U^b - \frac{W^{a-b} V^b}{r} \end{aligned} \right. + \sum_{b=-\infty}^{\infty} \left\{ \begin{aligned} & ib\kappa P^{a-b} U^b \\ & ib\kappa P^{a-b} V^b \\ & ib\kappa P^{a-b} W^b \end{aligned} \right.
\end{aligned}$$

Now, we are going to project on  $\psi$ , it may be a little complex, we will doing step by step.

#### A. Momentum $e^s$ term

First, deal with the  $e^s$  term:

$$\begin{aligned}
& -ia\kappa U^a + \frac{1}{1-\kappa r \cos \phi} \frac{\partial P^a}{\partial s} \\
& = \sum_{b=-\infty}^{\infty} term\mathcal{D}1 : -\frac{U^{a-b}}{1-\kappa r \cos \phi} \frac{\partial U^b}{\partial s} - V^{a-b} \frac{\partial U^b}{\partial r} - \frac{W^{a-b}}{r} \frac{\partial U^b}{\partial \theta} \\
& + \sum_{b=-\infty}^{\infty} term\mathcal{X}1 : \frac{\kappa \cos \phi}{1-\kappa r \cos \phi} U^{a-b} V^b - \frac{\kappa \sin \phi}{(1-\kappa r \cos \phi)} U^{a-b} W^b \\
& + ib\kappa P^{a-b} U^b \quad (40)
\end{aligned}$$

Multiply  $(1-\kappa r \cos \phi)$ , we have:

$$\begin{aligned}
& -ia\kappa(1-\kappa r \cos \phi) U^a + \frac{\partial P^a}{\partial s} \\
& = term\mathcal{D}1 : \sum_{b=-\infty}^{\infty} -U^{a-b} \frac{\partial U^b}{\partial s} - (1-\kappa r \cos \phi) V^{a-b} \frac{\partial U^b}{\partial r} - (1-\kappa r \cos \phi) \frac{W^{a-b}}{r} \frac{\partial U^b}{\partial \theta} \\
& + term\mathcal{X}1 : \sum_{b=-\infty}^{\infty} \kappa \cos \phi U^{a-b} V^b - \kappa \sin \phi U^{a-b} W^b + \\
& term\mathcal{P}1 : \sum_{b=-\infty}^{\infty} ib\kappa(1-\kappa r \cos \phi) P^{a-b} U^b \quad (41)
\end{aligned}$$

$\int \int XXr\psi_\alpha dr d\theta$ , we have:

$$\underline{RHS = \int_0^{2\pi} \int_0^h [term\mathcal{D}1 + term\mathcal{X}1 + term\mathcal{P}1] r\psi_\alpha dr d\theta} \quad (42)$$

1. the first  $\mathcal{D}1$  tems:

We ref the wiki [https](https://en.wikipedia.org/wiki/Leibniz_integral_rule) :

[en.wikipedia.org/wiki/Leibniz\\_integral\\_rule](https://en.wikipedia.org/wiki/Leibniz_integral_rule)

General form: Differentiation under the integral sign:

$$\frac{d}{dx} \left( \int_{a(x)}^{b(x)} f(x, t) dt \right) = f(x, b(x)) \cdot \frac{d}{dx} b(x) + f(x, a(x)) \cdot \frac{d}{dx} a(x) = \int_{a(x)}^{b(x)} \frac{d}{dx} f(x, t) dt \quad (43)$$

$$df = \frac{\partial f}{\partial x} dx + \frac{\partial f}{\partial y} dy \quad (44)$$

For partial difference, for a given  $\beta$ , the derivation of the fuction  $g(\alpha) = \int_{a(\alpha)}^{b(\beta)} f(x, \alpha) dx$  is

$$\frac{d}{d\alpha} \left( \int_{a(\alpha)}^{b(\beta)} f(x, \alpha) dx \right) = 0 + \frac{da(\alpha)}{d\alpha} f(a(\alpha), \alpha) = \int_{a(\alpha)}^{b(\beta)} \frac{\partial}{\partial \alpha} f(x, \alpha) dx \quad (45)$$

1.1

$$\begin{aligned} & \sum_{b=-\infty}^{\infty} \int_0^{2\pi} \int_0^h [-rU^{a-b} \frac{\partial U^b}{\partial s}] \psi_\alpha dr d\theta \\ &= \sum_{b=-\infty}^{\infty} - \int_0^{2\pi} \int_0^h \frac{\partial}{\partial s} [rU^{a-b} U^b \psi_\alpha] dr d\theta \\ & \quad + \int_0^{2\pi} \int_0^h U^b \frac{\partial}{\partial s} [rU^{a-b} \psi_\alpha] dr d\theta \\ &= \sum_{b=-\infty}^{\infty} - \frac{\partial}{\partial s} \int_0^{2\pi} \int_0^h [rU^{a-b} U^b \psi_\alpha] dr d\theta + \int_0^{2\pi} \frac{dh(s)}{ds} [rU^{a-b} U^b \psi_\alpha]_{r=h} d\theta \\ & \quad + \int_0^{2\pi} \int_0^h \frac{r \partial U^{a-b}}{\partial s} U^b \psi_\alpha dr d\theta \\ & \quad + \int_0^{2\pi} \int_0^h \frac{\partial \psi_\alpha}{\partial s} r U^{a-b} U^b dr d\theta \end{aligned} \quad (46)$$

here, we gives a relationship between  $U^a$  and  $V^a$  at the boundary which to dliminate  $V^a$  tems:

$$h' U^{a-b} = (1 - \kappa h \cos \phi) V^{a-b} \quad (47)$$

1.2

$$\begin{aligned}
& \sum_{b=-\infty}^{\infty} \int_0^{2\pi} \int_0^h [-(1 - \kappa r \cos \phi) V^{a-b} \frac{\partial U^b}{\partial r}] r \psi_\alpha dr d\theta \\
&= - \sum_{b=-\infty}^{\infty} \int_0^{2\pi} \int_0^h \frac{\partial(r(1 - \kappa r \cos \phi) V^{a-b} U^b \psi_\alpha)}{\partial r} dr d\theta \\
&\quad + \int_0^{2\pi} \int_0^h U^b \frac{\partial(r(1 - \kappa r \cos \phi) V^{a-b} \psi_\alpha)}{\partial r} dr d\theta \\
&= - \sum_{b=-\infty}^{\infty} \int_0^{2\pi} [(r(1 - \kappa r \cos \phi) V^{a-b} U^b) \psi_\alpha]_0^h d\theta \\
&\quad + \int_0^{2\pi} \int_0^h U^b \frac{\partial(r(1 - \kappa r \cos \phi) V^{a-b})}{\partial r} \psi_\alpha dr d\theta \\
&\quad + \int_0^{2\pi} \int_0^h U^b \frac{\partial(\psi_\alpha)}{\partial r} r(1 - \kappa r \cos \phi) V^{a-b} dr d\theta \\
&\quad = - \sum_{b=-\infty}^{\infty} \int_0^{2\pi} [(h h' U^{a-b} U^b) \psi_\alpha]_0^h d\theta \\
&\quad + \int_0^{2\pi} \int_0^h U^b \frac{\partial(r(1 - \kappa r \cos \phi) V^{a-b})}{\partial r} \psi_\alpha dr d\theta \\
&\quad + \int_0^{2\pi} \int_0^h U^b \frac{\partial(\psi_\alpha)}{\partial r} r(1 - \kappa r \cos \phi) V^{a-b} dr d\theta
\end{aligned} \tag{48}$$

1.3

$$\begin{aligned}
& \sum_{b=-\infty}^{\infty} \int_0^{2\pi} \int_0^h [-(1 - \kappa r \cos \phi) \frac{W^{a-b}}{r} \frac{\partial U^b}{\partial \theta}] r \psi_\alpha dr d\theta \\
&= - \sum_{b=-\infty}^{\infty} \int_0^{2\pi} \int_0^h \frac{\partial((1 - \kappa r \cos \phi) W^{a-b} U^b \psi_\alpha)}{\partial \theta} dr d\theta \\
&\quad + \int_0^{2\pi} \int_0^h U^b \frac{\partial((1 - \kappa r \cos \phi) W^{a-b})}{\partial \theta} \psi_\alpha dr d\theta \\
&\quad + \int_0^{2\pi} \int_0^h U^b \frac{\partial(\psi_\alpha)}{\partial \theta} ((1 - \kappa r \cos \phi) W^{a-b}) dr d\theta \\
&\quad = - \sum_{b=-\infty}^{\infty} \int_0^{2\pi} [(1 - \kappa r \cos \phi) W^{a-b} U^b \psi_\alpha]_0^{2\pi} dr \\
&\quad + \int_0^{2\pi} \int_0^h U^b \frac{\partial((1 - \kappa r \cos \phi) W^{a-b})}{\partial \theta} \psi_\alpha dr d\theta \\
&\quad + \int_0^{2\pi} \int_0^h U^b \frac{\partial(\psi_\alpha)}{\partial \theta} ((1 - \kappa r \cos \phi) W^{a-b}) dr d\theta \\
&= 0(\text{periodic}) + \int_0^{2\pi} \int_0^h U^b \frac{\partial((1 - \kappa r \cos \phi) W^{a-b})}{\partial \theta} \psi_\alpha dr d\theta \\
&\quad + \int_0^{2\pi} \int_0^h U^b \frac{\partial(\psi_\alpha)}{\partial \theta} ((1 - \kappa r \cos \phi) W^{a-b}) dr d\theta
\end{aligned} \tag{49}$$

Combine together:

$$\begin{aligned}
& \frac{\int_0^{2\pi} \int_0^h [term \mathcal{D}1] r \psi_\alpha dr d\theta}{\sum_{b=-\infty}^{\infty}} = \sum_{b=-\infty}^{\infty} \\
& \{ (\int_0^{2\pi} \int_0^h \frac{\partial \psi_\alpha}{\partial s} r U^{a-b} U^b dr d\theta \\
& + \int_0^{2\pi} \int_0^h \frac{\partial(\psi_\alpha)}{\partial r} r (1 - \kappa r \cos \phi) V^{a-b} U^b dr d\theta \\
& + \int_0^{2\pi} \int_0^h \frac{\partial(\psi_\alpha)}{\partial \theta} ((1 - \kappa r \cos \phi) W^{a-b} U^b) dr d\theta) \\
& + (\int_0^{2\pi} \int_0^h U^b \frac{\partial U^{a-b}}{\partial s} r \psi_\alpha dr d\theta \\
& + \int_0^{2\pi} \int_0^h U^b \frac{\partial(r(1 - \kappa r \cos \phi) V^{a-b})}{\partial r} \psi_\alpha dr d\theta \\
& + \int_0^{2\pi} \int_0^h U^b \frac{\partial((1 - \kappa r \cos \phi) W^{a-b})}{\partial \theta} \psi_\alpha dr d\theta) \\
& - \frac{\partial}{\partial s} \int_0^{2\pi} \int_0^h [r U^{a-b} U^b \psi_\alpha] dr d\theta \}
\end{aligned} \tag{50}$$

We apply eq 5, find that:

$$\begin{aligned}
& -i(a-b)\kappa r(1 - \kappa r \cos(\phi)) P^{a-b} + \left[ \frac{\partial(U^{a-b} r)}{\partial s} + \frac{\partial(V^{a-b} r(1 - \kappa r \cos(\phi)))}{\partial r} + \frac{\partial(W^{a-b}(1 - \kappa r \cos(\phi)))}{\partial \theta} \right] \\
& = o(M^2)
\end{aligned} \tag{51}$$

We have the second terms in eq(31) are equal to:

$$\begin{aligned}
& \int_0^{2\pi} \int_0^h U^b [-i(a-b)\kappa r(1 - \kappa r \cos(\phi)) P^{a-b}] \psi_\alpha dr d\theta \\
& = i(a-b)\kappa \Psi_{\alpha\beta\gamma} [r(1 - \kappa r \cos \phi)] P_\beta^{a-b} U_\gamma^b
\end{aligned} \tag{52}$$

And, the longitudinal derivation s can also be expand about the duct modes, with note

$[r], (\theta), \{s\}$ :

$$\begin{aligned}
& \frac{\partial}{\partial s} \int_0^{2\pi} \int_0^h [r U^{a-b} U^b \psi_\alpha] dr d\theta \\
& = \frac{\partial}{\partial s} \int_0^{2\pi} \int_0^h [r \psi_\beta \psi_\gamma \psi_\alpha] U_\beta^{a-b} U_\gamma^b dr d\theta \\
& = \frac{\partial}{\partial s} (\int_0^{2\pi} \int_0^h [r \psi_\beta \psi_\gamma \psi_\alpha] dr d\theta) U_\beta^{a-b} U_\gamma^b \\
& \quad + \frac{\partial U_\beta^{a-b} U_\gamma^b}{\partial s} \int_0^{2\pi} \int_0^h [r \psi_\beta \psi_\gamma \psi_\alpha] dr d\theta \\
& = \frac{\partial}{\partial s} (\int_0^{2\pi} \int_0^h [r \psi_\beta \psi_\gamma \psi_\alpha] dr d\theta) U_\beta^{a-b} U_\gamma^b \\
& \quad + (\frac{dU_\beta^{a-b}}{ds} U_\gamma^b + \frac{dU_\gamma^b}{ds} U_\beta^{a-b}) \int_0^{2\pi} \int_0^h [r \psi_\beta \psi_\gamma \psi_\alpha] dr d\theta
\end{aligned} \tag{53}$$

2. the second  $\mathcal{X}1$  tems:

$$\begin{aligned}
term\mathcal{X}1 &: \sum_{b=-\infty}^{\infty} \kappa \cos\phi U^{a-b} V^b - \kappa \sin\phi U^{a-b} W^b \\
&\sum_{b=-\infty}^{\infty} \int_0^{2\pi} \int_0^h [\kappa \cos\phi U^{a-b} V^b - \kappa \sin\phi U^{a-b} W^b] r \psi_\alpha dr d\theta \\
&= \kappa \Psi_{\alpha\beta\gamma} [r \cos\phi] U_\beta^{a-b} V_\gamma^b - \kappa \Psi_{\alpha\beta\gamma} [r \sin\phi] U_\beta^{a-b} W_\gamma^b
\end{aligned} \tag{54}$$

3. the second  $\mathcal{P}1$  tems:

$$\begin{aligned}
term\mathcal{P}1 &: \sum_{b=-\infty}^{\infty} ib\kappa(1 - \kappa r \cos\phi) P^{a-b} U^b \\
&\sum_{b=-\infty}^{\infty} \int_0^{2\pi} \int_0^h [ib\kappa(1 - \kappa r \cos\phi) P^{a-b} U^b] r \psi_\alpha dr d\theta \\
&= ib\kappa \Psi_{\alpha\beta\gamma} [r(1 - \kappa r \cos\phi)] P_\beta^{a-b} U_\gamma^b
\end{aligned} \tag{55}$$

4. The LHS terms:

$$\frac{\partial P^a}{\partial s} - ia\kappa(1 - \kappa r \cos\phi) U^a$$

From 1.1 as example, we know that

$$\begin{aligned}
&\int_0^{2\pi} \int_0^h \frac{\partial}{\partial s} [r U^{a-b} U^b \psi_\alpha] dr d\theta \\
&= \frac{\partial}{\partial s} \int_0^{2\pi} \int_0^h [r U^{a-b} U^b \psi_\alpha] dr d\theta - \int_0^{2\pi} \frac{dh(s)}{ds} [r U^{a-b} U^b \psi_\alpha]_{r=h} d\theta
\end{aligned} \tag{56}$$

4.1

$$\begin{aligned}
&\int_0^{2\pi} \int_0^h \left[ \frac{\partial P^a}{\partial s} \right] r \psi_\alpha dr d\theta \\
&= \int_0^{2\pi} \int_0^h \left[ \frac{\partial(P_\beta^a \psi_\beta)}{\partial s} \right] r \psi_\alpha dr d\theta \\
&= \int_0^{2\pi} \int_0^h \left[ \frac{\partial(P_\beta^a \psi_\beta)}{\partial s} r \psi_\alpha \right] dr d\theta - \int_0^{2\pi} \int_0^h \left[ \frac{\partial(\psi_\alpha)}{\partial s} \right] r \psi_\beta dr d\theta P_\beta^a \\
&= \frac{\partial}{\partial s} \int_0^{2\pi} \int_0^h (P_\beta^a \psi_\beta) r \psi_\alpha dr d\theta - \frac{dh(s)}{ds} [P_\beta^a \psi_\beta r \psi_\alpha]_{r=h} - \int_0^{2\pi} \int_0^h \left[ \frac{\partial(\psi_\alpha)}{\partial s} \right] r \psi_\beta dr d\theta P_\beta^a \\
&= \frac{\partial}{\partial s} (P_\beta^a \delta_{\alpha\beta}) - \int_0^{2\pi} \frac{dh(s)}{ds} [P_\beta^a \psi_\beta r \psi_\alpha]_{r=h} d\theta - \int_0^{2\pi} \int_0^h \left[ \frac{\partial(\psi_\alpha)}{\partial s} \right] r \psi_\beta dr d\theta P_\beta^a \\
&= \frac{d}{ds} P_\alpha^a - \int_0^{2\pi} \frac{dh(s)}{ds} [P_\beta^a \psi_\beta r \psi_\alpha]_{r=h} d\theta - \int_0^{2\pi} \int_0^h \left[ \frac{\partial(\psi_\alpha)}{\partial s} \right] r \psi_\beta dr d\theta P_\beta^a
\end{aligned} \tag{57}$$

$$= \frac{d}{ds} P_\alpha^a - \int_0^{2\pi} \int_0^h \frac{\partial \psi_\beta \psi_\alpha}{\partial r} h h' dr d\theta P_\beta^a - \int_0^{2\pi} \int_0^h \left[ \frac{\partial(\psi_\alpha)}{\partial s} \right] r \psi_\beta dr d\theta P_\beta^a$$

4.2

$$\begin{aligned} & \int_0^{2\pi} \int_0^h [-ia\kappa(1 - \kappa r \cos\phi) U^a] r \psi_\alpha dr d\theta \\ &= -ia\kappa \Psi_{\alpha\beta} [r(1 - \kappa r \cos\phi)] U_\beta^a \end{aligned} \quad (58)$$

Finally, putting all together becomes:

$$\begin{aligned} & \frac{d}{ds} P_\alpha^a - \int_0^{2\pi} \frac{dh(s)}{ds} [P_\beta^a \psi_\beta r \psi_\alpha]_{r=h} d\theta - \int_0^{2\pi} \int_0^h \left[ \frac{\partial(\psi_\alpha)}{\partial s} \right] r \psi_\beta dr d\theta P_\beta^a - ia\kappa \Psi_{\alpha\beta} [r(1 - \kappa r \cos\phi)] U_\beta^a \\ &= \frac{d}{ds} P_\alpha^a - ia\kappa \Psi_{\alpha\beta} [r(1 - \kappa r \cos\phi)] U_\beta^a - \int_0^{2\pi} h h' [P_\beta^a \psi_\beta \psi_\alpha]_{r=h} d\theta - \Psi_{\{\alpha\}\beta} [r] P_\beta^a \\ &= \sum_{b=-\infty}^{\infty} \\ & \quad (eq31) : \left\{ \left( \int_0^{2\pi} \int_0^h \frac{\partial \psi_\alpha}{\partial s} r U^{a-b} U^b dr d\theta \right. \right. \\ & \quad \left. \left. + \int_0^{2\pi} \int_0^h \frac{\partial(\psi_\alpha)}{\partial r} r (1 - \kappa r \cos\phi) V^{a-b} U^b dr d\theta \right. \right. \\ & \quad \left. \left. + (eq33) : i(a-b)\kappa \Psi_{\alpha\beta\gamma} [r(1 - \kappa r \cos\phi)] P_\beta^{a-b} U_\gamma^b \right. \right. \\ & \quad \left. \left. eq(34) : -\frac{\partial}{\partial s} \left( \int_0^{2\pi} \int_0^h [r \psi_\beta \psi_\gamma \psi_\alpha] dr d\theta \right) U_\beta^{a-b} U_\gamma^b \right. \right. \\ & \quad \left. \left. - \left( \frac{dU_\beta^{a-b}}{ds} U_\gamma^b + \frac{dU_\gamma^b}{ds} U_\beta^{a-b} \right) \int_0^{2\pi} \int_0^h [r \psi_\beta \psi_\gamma \psi_\alpha] dr d\theta \right. \right. \\ & \quad \left. \left. + eq(35) : \kappa \Psi_{\alpha\beta\gamma} [r \cos\phi] U_\beta^{a-b} V_\gamma^b - \kappa \Psi_{\alpha\beta\gamma} [r \sin\phi] U_\beta^{a-b} W_\gamma^b \right. \right. \\ & \quad \left. \left. + eq(36) : ib\kappa \Psi_{\alpha\beta\gamma} [r(1 - \kappa r \cos\phi)] P_\beta^{a-b} U_\gamma^b \right. \right. \\ & \quad \left. = (abbreviation) : \right. \\ & \quad \Psi_{\{\alpha\}\beta\gamma} [r] U_\beta^{a-b} U_\gamma^a + \Psi_{[\alpha]\beta\gamma} [r(1 - \kappa r \cos\phi)] V_\beta^{a-b} U_\gamma^a + \Psi_{(\alpha)\beta\gamma} [(1 - \kappa r \cos\phi)] W_\beta^{a-b} U_\gamma^a \\ & \quad + i(a-b)\kappa \Psi_{\alpha\beta\gamma} [r(1 - \kappa r \cos\phi)] P_\beta^{a-b} U_\gamma^b \\ & \quad - \frac{\partial}{\partial s} (\Psi_{\alpha\beta\gamma} [r] U_\beta^{a-b} U_\gamma^b - \Psi_{\alpha\beta\gamma} [r] \left( \frac{dU_\beta^{a-b}}{ds} U_\gamma^b + \frac{dU_\gamma^b}{ds} U_\beta^{a-b} \right) \\ & \quad + \kappa \Psi_{\alpha\beta\gamma} [r \cos\phi] U_\beta^{a-b} V_\gamma^b - \kappa \Psi_{\alpha\beta\gamma} [r \sin\phi] U_\beta^{a-b} W_\gamma^b \\ & \quad \left. + ib\kappa \Psi_{\alpha\beta\gamma} [r(1 - \kappa r \cos\phi)] P_\beta^{a-b} U_\gamma^b \right) \end{aligned} \quad (59)$$

To be conclude, with the  $e^s$  term:

$$\begin{aligned}
& -ia\kappa U^a + \frac{1}{1-\kappa r \cos\phi} \frac{\partial P^a}{\partial s} \\
= & \sum_{b=-\infty}^{\infty} \text{term}\mathcal{D}1 : -\frac{U^{a-b}}{1-\kappa r \cos\phi} \frac{\partial U^b}{\partial s} - V^{a-b} \frac{\partial U^b}{\partial r} - \frac{W^{a-b}}{r} \frac{\partial U^b}{\partial \theta} \\
& + \sum_{b=-\infty}^{\infty} \text{term}\mathcal{X}1 : \frac{\kappa \cos\phi}{1-\kappa r \cos\phi} U^{a-b} V^b - \frac{\kappa \sin\phi}{(1-\kappa r \cos\phi)} U^{a-b} W^b \\
& + \sum_{b=-\infty}^{\infty} \text{term}\mathcal{P}1 : ib\kappa P^{a-b} U^b
\end{aligned} \tag{60}$$

We have:

$$\begin{aligned}
& -ia\kappa \Psi_{\alpha\beta}[r(1-\kappa r \cos\phi)] U_{\beta}^a + \frac{d}{ds} P_{\alpha}^a - \int_0^{2\pi} hh'[\psi_{\beta}\psi_{\alpha}]_{r=h} d\theta P_{\beta}^a - \Psi_{\{\alpha\}\beta}[r] P_{\beta}^a \\
= & \underline{\text{term}\mathcal{D}1} : \Psi_{\{\alpha\}\beta\gamma}[r] U_{\beta}^{a-b} U_{\gamma}^a + \Psi_{[\alpha]\beta\gamma}[r(1-\kappa r \cos\phi)] V_{\beta}^{a-b} U_{\gamma}^a + \Psi_{(\alpha)\beta\gamma}[(1-\kappa r \cos\phi)] W_{\beta}^{a-b} U_{\gamma}^a \\
& + \underline{\text{term}(\mathcal{D}1 + \mathcal{P}1)} : i(a)\kappa \Psi_{\alpha\beta\gamma}[r(1-\kappa r \cos\phi)] P_{\beta}^{a-b} U_{\gamma}^b \\
& - \underline{\text{term}\mathcal{D}1} : \frac{\partial}{\partial s} (\Psi_{\alpha\beta\gamma}[r] U_{\beta}^{a-b} U_{\gamma}^b - \Psi_{\alpha\beta\gamma}[r] (\frac{dU_{\beta}^{a-b}}{ds} U_{\gamma}^b + \frac{dU_{\gamma}^b}{ds} U_{\beta}^{a-b})) \\
& + \underline{\text{term}\mathcal{X}1} : \kappa \Psi_{\alpha\beta\gamma}[r \cos\phi] U_{\beta}^{a-b} V_{\gamma}^b - \kappa \Psi_{\alpha\beta\gamma}[r \sin\phi] U_{\beta}^{a-b} W_{\gamma}^b
\end{aligned} \tag{61}$$

## B. Momentum $e^r$ term

Second, deal with the  $e^r$  term:

$$\begin{aligned}
& -ia\kappa V^a + \frac{\partial P^a}{\partial r} \\
= & \sum_{b=-\infty}^{\infty} \text{term}\mathcal{D}2 : -\frac{U^{a-b}}{1-\kappa r \cos\phi} \frac{\partial V^b}{\partial s} - V^{a-b} \frac{\partial V^b}{\partial r} - \frac{W^{a-b}}{r} \frac{\partial V^b}{\partial \theta} \\
& + \sum_{b=-\infty}^{\infty} \text{term}\mathcal{X}2 : \frac{W^{a-b} W^b}{r} - \frac{\kappa \cos\phi}{(1-\kappa r \cos\phi)} U^{a-b} U^b \\
& + \text{term}\mathcal{P}2 : \sum_{b=-\infty}^{\infty} ib\kappa P^{a-b} V^b
\end{aligned} \tag{62}$$

LHS-2:  $\frac{\partial P^a}{\partial r}(1 - \kappa r \cos \phi)$

$$\begin{aligned}
& \int_0^{2\pi} \int_0^h \left[ \frac{\partial P^a}{\partial r}(1 - \kappa r \cos \phi) \right] r \psi_\alpha dr d\theta \\
&= \int_0^{2\pi} \int_0^h \left[ \frac{\partial \psi_\beta (1 - \kappa r \cos \phi)}{\partial r} r \psi_\alpha \right] dr d\theta P_\beta^a - \int_0^{2\pi} \int_0^h \left[ \frac{\partial \psi_\alpha (1 - \kappa r \cos \phi)}{\partial r} r \right] \psi_\beta dr d\theta P_\beta^a \\
&= \int_0^{2\pi} \int_0^h \left[ \frac{\partial \psi_\beta (1 - \kappa r \cos \phi)}{\partial r} r \psi_\alpha \right] dr d\theta P_\beta^a \\
&- \int_0^{2\pi} \int_0^h \left[ \frac{\partial \psi_\alpha}{\partial r} \right] (1 - \kappa r \cos \phi) r \psi_\beta dr d\theta P_\beta^a - \int_0^{2\pi} \int_0^h \left[ \frac{\partial (1 - \kappa r \cos \phi)}{\partial r} r \right] \psi_\alpha \psi_\beta dr d\theta P_\beta^a \quad (63) \\
&= \int_0^{2\pi} [\psi_\alpha \psi_\beta r (1 - \kappa r \cos \phi)]_0^h d\theta P_\beta^a \\
&- \int_0^{2\pi} \int_0^h \left[ \frac{\partial \psi_\alpha}{\partial r} \right] (1 - \kappa r \cos \phi) r \psi_\beta dr d\theta P_\beta^a - \int_0^{2\pi} \int_0^h [1 - 2\kappa r \cos \phi] \psi_\alpha \psi_\beta dr d\theta P_\beta^a \\
&= \int_0^{2\pi} [\psi_\alpha \psi_\beta r (1 - \kappa r \cos \phi)]_0^h d\theta P_\beta^a - \Psi_{[\alpha]\beta} [r(1 - \kappa r \cos \phi)] P_\beta^a - \Psi_{\alpha\beta} [1 - 2\kappa r \cos \phi] P_\beta^a
\end{aligned}$$

The derivation of *termD2* is identical to A, we are not prove it again. *TermP2* also could be combine with the part separated term of *termD2* with  $V^b$ . *TermX2* is also easy to derive.

Thus, we have the final equation:

$$\begin{aligned}
& -ia\kappa\Psi_{\alpha\beta}[r(1 - \kappa r \cos \phi)]V_\beta^a \\
& \int_0^{2\pi} [\psi_\alpha \psi_\beta r (1 - \kappa r \cos \phi)]_0^h d\theta P_\beta^a - \Psi_{[\alpha]\beta} [r(1 - \kappa r \cos \phi)] P_\beta^a - \Psi_{\alpha\beta} [1 - 2\kappa r \cos \phi] P_\beta^a \\
&= \underline{termD2} : \Psi_{\{\alpha\}\beta\gamma} [r] U_\beta^{a-b} V_\gamma^a + \Psi_{[\alpha]\beta\gamma} [r(1 - \kappa r \cos \phi)] V_\beta^{a-b} V_\gamma^a + \Psi_{(\alpha)\beta\gamma} [(1 - \kappa r \cos \phi)] W_\beta^{a-b} V_\gamma^a \\
& \quad + \underline{term(D2 + P2)} : i(a)\kappa\Psi_{\alpha\beta\gamma} [r(1 - \kappa r \cos \phi)] P_\beta^{a-b} V_\gamma^b \\
& \quad + \underline{termD2} : -\frac{\partial}{\partial s} (\Psi_{\alpha\beta\gamma} [r] U_\beta^{a-b} V_\gamma^b - \Psi_{\alpha\beta\gamma} [r] (\frac{dU_\beta^{a-b}}{ds} V_\gamma^b + \frac{dV_\gamma^b}{ds} U_\beta^{a-b})) \\
& \quad + \underline{termX2} : \Psi_{\alpha\beta\gamma} [1 - \kappa r \cos \phi] W_\beta^{a-b} W_\gamma^b - \kappa\Psi_{\alpha\beta\gamma} [r \cos \phi] U_\beta^{a-b} U_\gamma^b \quad (64)
\end{aligned}$$

### C. Momentum $e^\theta$ term

Third, deal with the  $e^\theta$  term:



$$\begin{aligned}
& -ia\kappa W^a + \frac{1}{r} \frac{\partial P^a}{\partial \theta} \\
= & \sum_{b=-\infty}^{\infty} \text{term}\mathcal{D}3 : -\frac{U^{a-b}}{1-\kappa r \cos \phi} \frac{\partial W^b}{\partial s} - V^{a-b} \frac{\partial W^b}{\partial r} - \frac{W^{a-b}}{r} \frac{\partial W^b}{\partial \theta} \\
& + \sum_{b=-\infty}^{\infty} \text{term}\mathcal{X}3 : \frac{\kappa \sin \phi}{(1-\kappa r \cos \phi)} U^{a-b} V^b - \frac{W^{a-b} V^b}{r} \\
& + \text{term}\mathcal{P}3 : \sum_{b=-\infty}^{\infty} ib\kappa P^{a-b} W^b
\end{aligned} \tag{65}$$

$$\begin{aligned}
\text{LHS-2: } & \frac{\partial P^a}{\partial \theta} \frac{(1-\kappa r \cos \phi)}{r} \\
= & \int_0^{2\pi} \int_0^h \left[ \frac{\partial P^a}{\partial \theta} \frac{(1-\kappa r \cos \phi)}{r} \right] r \psi_\alpha dr d\theta \\
= & \int_0^{2\pi} \int_0^h \left[ \frac{\partial \psi_\beta (1-\kappa r \cos \phi)}{\partial \theta} \psi_\alpha \right] dr d\theta P_\beta^a - \int_0^{2\pi} \int_0^h \left[ \frac{\partial \psi_\alpha (1-\kappa r \cos \phi)}{\partial \theta} \right] \psi_\beta dr d\theta P_\beta^a \\
= & 0 - \int_0^{2\pi} \int_0^h \left[ \frac{\partial \psi_\alpha}{\partial \theta} \right] (1-\kappa r \cos \phi) \psi_\beta dr d\theta P_\beta^a - \int_0^{2\pi} \int_0^h \left[ \frac{\partial (1-\kappa r \cos \phi)}{\partial \theta} \right] \psi_\alpha \psi_\beta dr d\theta P_\beta^a \\
= & - \int_0^{2\pi} \int_0^h \left[ \frac{\partial \psi_\alpha}{\partial \theta} \right] (1-\kappa r \cos \phi) \psi_\beta dr d\theta P_\beta^a + \kappa \int_0^{2\pi} \int_0^h [r \sin \phi] \psi_\alpha \psi_\beta dr d\theta P_\beta^a \\
= & -\Psi_{(\alpha)\beta} [(1-\kappa r \cos \phi)] P_\beta^a - \kappa \Psi_{\alpha\beta} [r \sin \phi] P_\beta^a
\end{aligned} \tag{66}$$

The derivation of  $\text{term}\mathcal{D}3$  is identical to A, we are not prove it again.  $\text{Term}\mathcal{P}3$  also could be combine with the part separated term of  $\text{term}\mathcal{D}3$  with  $W^b$ .  $\text{Term}\mathcal{X}3$  is also easy to derive.

Thus, we have the final equation:

$$\begin{aligned}
& -ia\kappa \Psi_{\alpha\beta} [r(1-\kappa r \cos \phi)] W_\beta^a \\
& -\Psi_{(\alpha)\beta} [(1-\kappa r \cos \phi)] P_\beta^a - \kappa \Psi_{\alpha\beta} [r \sin \phi] P_\beta^a \\
= & \underline{\text{term}\mathcal{D}2} : \Psi_{\{\alpha\}\beta\gamma} [r] U_\beta^{a-b} W_\gamma^a + \Psi_{[\alpha]\beta\gamma} [r(1-\kappa r \cos \phi)] V_\beta^{a-b} W_\gamma^a + \Psi_{(\alpha)\beta\gamma} [(1-\kappa r \cos \phi)] W_\beta^{a-b} W_\gamma^a \\
& + \underline{\text{term}(D2 + \mathcal{P}2)} : i(a)\kappa \Psi_{\alpha\beta\gamma} [r(1-\kappa r \cos \phi)] P_\beta^{a-b} W_\gamma^b \\
& + \underline{\text{term}\mathcal{D}2} : -\frac{\partial}{\partial s} (\Psi_{\alpha\beta\gamma} [r] U_\beta^{a-b} V_\gamma^b - \Psi_{\alpha\beta\gamma} [r] (\frac{dU_\beta^{a-b}}{ds} W_\gamma^b + \frac{dW_\gamma^b}{ds} U_\beta^{a-b})) \\
& + \underline{\text{term}\mathcal{X}2} : \kappa \Psi_{\alpha\beta\gamma} [r \sin \phi] U_\beta^{a-b} V_\gamma^b - \Psi_{\alpha\beta\gamma} [1-\kappa r \cos \phi] W_\beta^{a-b} V_\gamma^b
\end{aligned} \tag{67}$$

#### IV. Merge the four equations and eliminate the $V_\gamma^b$ and $W_\gamma^b$

##### A. nonlinear term

we have to re-derive the momentum equation with multiply  $(1 - \kappa r \cos \phi)$ :

$$\begin{aligned}
& -ia\kappa V^a + \frac{\partial P^a}{\partial r} \\
= & \sum_{b=-\infty}^{\infty} \text{term}\mathcal{D}2 : -\frac{U^{a-b}}{1 - \kappa r \cos \phi} \frac{\partial V^b}{\partial s} - V^{a-b} \frac{\partial V^b}{\partial r} - \frac{W^{a-b}}{r} \frac{\partial V^b}{\partial \theta} \\
& + \sum_{b=-\infty}^{\infty} \text{term}\mathcal{X}2 : \frac{W^{a-b} W^b}{r} - \frac{\kappa \cos \phi}{(1 - \kappa r \cos \phi)} U^{a-b} U^b \\
& + \text{term}\mathcal{P}2 : \sum_{b=-\infty}^{\infty} ib\kappa P^{a-b} V^b
\end{aligned} \tag{68}$$

LHS-2:  $\frac{\partial P^a}{\partial r}$

$$\begin{aligned}
& \int_0^{2\pi} \int_0^h \left[ \frac{\partial P^a}{\partial r} \right] r \psi_\alpha dr d\theta \\
= & \int_0^{2\pi} [r \psi_\alpha \psi_\beta]_0^h d\theta P_\beta^a - \int \int \psi_\alpha \psi_\beta dr d\theta P_\beta^a - \int \int \frac{\partial \psi_\alpha}{\partial r} \psi_\beta r dr d\theta P_\beta^a
\end{aligned} \tag{69}$$

Thus, we have the final equation:

$$\begin{aligned}
& -ia\kappa \Psi_{\alpha\beta}[r] V_\beta^a + \int_0^{2\pi} [\psi_\alpha \psi_\beta r]_0^h d\theta P_\beta^a - \Psi_{[\alpha]\beta}[r] P_\beta^a a - \Psi_{\alpha\beta} P_\beta^a \\
= & \underline{\text{term}\mathcal{D}2} : \Psi_{\{\alpha\}\beta\gamma}[r] U_\beta^{a-b} V_\gamma^a + \Psi_{[\alpha]\beta\gamma}[r] V_\beta^{a-b} V_\gamma^a + \Psi_{(\alpha)\beta\gamma} W_\beta^{a-b} V_\gamma^a \\
& + \underline{\text{term}(\mathcal{D}2 + \mathcal{P}2)} : i(a)\kappa \Psi_{\alpha\beta\gamma}[r] P_\beta^{a-b} V_\gamma^b \\
& + \underline{\text{term}\mathcal{D}2} : -\frac{\partial}{\partial s} (\Psi_{\alpha\beta\gamma}[r] U_\beta^{a-b} U_\gamma^b - \Psi_{\alpha\beta\gamma}[r] (\frac{dU_\beta^{a-b}}{ds} V_\gamma^b + \frac{dV_\gamma^b}{ds} U_\beta^{a-b}))_{\text{error}} \\
& + \underline{\text{term}\mathcal{X}2} : \kappa \Psi_{\alpha\beta\gamma} W_\beta^{a-b} W_\gamma^b
\end{aligned} \tag{70}$$

##### B. $V_\alpha^a$ & $W_\alpha^a$ for RHS

Using the linear relationships:

$$\begin{aligned}
& ia\kappa V^a = \frac{\partial P^a}{\partial r} \\
& := \int \int ia\kappa V_\beta^a \psi_\beta r \psi_\alpha dr d\theta = \int \int \frac{\partial P_\beta^a \psi_\beta}{\partial r} r \psi_\alpha dr d\theta \\
= & ia\kappa V_\beta^a \delta_{\alpha\beta} = \Psi_{\alpha[\beta]}[r] P_\beta^a = \int_0^{2\pi} [r \psi_\alpha \psi_\beta]_0^h d\theta P_\beta^a - \int \int \psi_\alpha \psi_\beta dr d\theta P_\beta^a - \int \int \frac{\partial \psi_\alpha}{\partial r} \psi_\beta r dr d\theta P_\beta^a
\end{aligned} \tag{71}$$

$$\begin{aligned}
iakW^a &= \frac{1}{r} \frac{\partial P^a}{\partial \theta} \\
:= \int \int iakW_\beta^a \psi_\beta r \psi_\alpha dr d\theta &= \int \int \frac{\partial P_\beta^a \psi_\beta}{\partial \theta} \frac{1}{r} r \psi_\alpha dr d\theta \\
&= iakW_\beta^a \delta_{\alpha\beta} = \Psi_{\alpha(\beta)}[r]P_\beta^a = 0 - \Psi_{(\alpha)\beta}[r]P_\beta^a
\end{aligned} \tag{72}$$

Thus, we can establish relationships between the tranverse modes and pressure modes (no summation over  $\alpha$ )

$$\underline{V_\alpha^a = \frac{1}{iak} \left[ \int_0^{2\pi} [r\psi_\alpha \psi_\beta]_0^h d\theta - \Psi_{\alpha\beta} - \Psi_{[\alpha]\beta}[r] \right] P_\beta^a = \mathbf{V}_{\alpha\beta}^a P_\beta^a} \tag{73}$$

$$\underline{W_\alpha^a = -\frac{1}{iak} \Psi_{(\alpha)\beta} P_\beta^a = \mathbf{W}_{\alpha\beta}^a P_\beta^a} \tag{74}$$

**C.**  $\frac{d}{ds} V_\alpha^a$  &  $\frac{d}{ds} W_\alpha^a$  for RHS

We also require modal expressions for  $\frac{d}{ds} V_\alpha^a$  and  $\frac{d}{ds} W_\alpha^a$ .

We differentiate eq71 with respect to  $s$ :

$$\begin{aligned}
\frac{\partial V^a}{\partial s} &= \frac{1}{iak} \frac{\partial^2 P^a}{\partial s \partial r} \\
&= \frac{\partial}{\partial r} ((1 - \kappa r \cos \phi) U^a)
\end{aligned} \tag{75}$$

where we have used symmetry of mixed partials and the linear expression for  $\frac{\partial P^a}{\partial s}$  from eq 21.

From 1.1 as example, we know that

$$\begin{aligned}
&\int_0^{2\pi} \int_0^h \frac{\partial}{\partial s} [r U^{a-b} U^b \psi_\alpha] dr d\theta \\
&= \frac{\partial}{\partial s} \int_0^{2\pi} \int_0^h [r U^{a-b} U^b \psi_\alpha] dr d\theta - \int_0^{2\pi} \frac{dh(s)}{ds} [r U^{a-b} U^b \psi_\alpha]_{r=h} d\theta
\end{aligned} \tag{76}$$

here, we gives a relationship between  $U^a$  and  $V^a$  at the boundary which to dliminate  $V^a$  tems:

$$h' U_\beta^a = (1 - \kappa h \cos \phi) V_\beta^a \tag{77}$$

Multiplying this expression by  $r\phi_\alpha$  and integrating across section of the duct, we obtain:

$$\begin{aligned}
& \int_0^{2\pi} \int_0^h \frac{\partial V^a}{\partial s} r \psi_\alpha dr d\theta = \int_0^{2\pi} \int_0^h \frac{\partial}{\partial r} ((1 - \kappa r \cos \phi) U^a) r \psi_\alpha dr d\theta \\
& LHS := \int_0^{2\pi} \int_0^h \frac{\partial [V_\beta^a \psi_\beta r \psi_\alpha]}{\partial s} dr d\theta - \int_0^{2\pi} \int_0^h \frac{\partial r \psi_\alpha}{\partial s} \psi_\beta dr d\theta V_\beta^a \\
& = \frac{\partial}{\partial s} \int_0^{2\pi} \int_0^h [V_\beta^a \psi_\beta r \psi_\alpha] dr d\theta - \int_0^{2\pi} \frac{dh(s)}{ds} [V_\beta^a \psi_\beta r \psi_\alpha]_0^h d\theta - \int_0^{2\pi} \int_0^h \frac{\partial \psi_\alpha}{\partial s} \psi_\beta r dr d\theta V_\beta^a \\
& = \frac{\partial}{\partial s} V_\beta^a \delta_{\alpha\beta} - \int_0^{2\pi} \frac{h'^2}{1 - \kappa h \cos \phi} [r \psi_\beta \psi_\alpha]_0^h d\theta U_\beta^a - \Psi_{\{\alpha\}\beta}[r] V_\beta^a \\
& = \frac{\partial}{\partial s} \int_0^{2\pi} \int_0^h [V_\beta^a \psi_\beta r \psi_\alpha] dr d\theta - \int_0^{2\pi} \frac{dh(s)}{ds} [V_\beta^a \psi_\beta r \psi_\alpha]_0^h d\theta - \int_0^{2\pi} \int_0^h \frac{\partial \psi_\alpha}{\partial s} \psi_\beta r dr d\theta V_\beta^a \\
& = \frac{d}{ds} V_\alpha^a - \int_0^{2\pi} \frac{h'^2}{1 - \kappa h \cos \phi} [r \psi_\beta \psi_\alpha]_0^h d\theta U_\beta^a - \Psi_{\{\alpha\}\beta}[r] V_\beta^a \\
& RHS := \int_0^{2\pi} \int_0^h \frac{\partial}{\partial r} ((1 - \kappa r \cos \phi) U_\beta^a \psi_\beta r \psi_\alpha) dr d\theta - \int_0^{2\pi} \int_0^h \frac{\partial (r \psi_\alpha)}{\partial r} (1 - \kappa r \cos \phi) U_\beta^a \psi_\beta dr d\theta \\
& = \int_0^{2\pi} [r(1 - \kappa r \cos \phi) \psi_\beta \psi_\alpha]_0^h d\theta U_\beta^a - \int_0^{2\pi} \int_0^h \frac{\partial \psi_\alpha}{\partial r} r(1 - \kappa r \cos \phi) \psi_\beta dr d\theta U_\beta^a - \int_0^{2\pi} \int_0^h (1 - \kappa r \cos \phi) \psi_\alpha \psi_\beta dr d\theta U_\beta^a \\
& = \int_0^{2\pi} [r(1 - \kappa r \cos \phi) \psi_\beta \psi_\alpha]_0^h d\theta U_\beta^a - \Psi_{[\alpha]\beta}[r(1 - \kappa r \cos \phi)] U_\beta^a - \Psi_{\alpha\beta}[(1 - \kappa r \cos \phi)] U_\beta^a \\
& \quad (78)
\end{aligned}$$

Thus, LHS=RHS, we have:

$$\begin{aligned}
& \underline{\underline{\frac{d}{ds} V_\alpha^a = \int_0^{2\pi} \frac{h'^2}{1 - \kappa h \cos \phi} [r \psi_\beta \psi_\alpha]_0^h d\theta U_\beta^a + \Psi_{\{\alpha\}\beta}[r] V_\beta^a}} \\
& + \underline{\underline{\int_0^{2\pi} [r(1 - \kappa r \cos \phi) \psi_\beta \psi_\alpha]_0^h d\theta U_\beta^a - \Psi_{[\alpha]\beta}[r(1 - \kappa r \cos \phi)] U_\beta^a - \Psi_{\alpha\beta}[(1 - \kappa r \cos \phi)] U_\beta^a}} \\
& \quad (79)
\end{aligned}$$

Similarly for  $W^a$ , differentiating eq50 with respect to s and substituting the linear expression

for  $\frac{\partial P^a}{\partial s}$  by eq21:

$$\begin{aligned}
& \frac{\partial W^a}{\partial s} = \frac{1}{ia\kappa} \frac{\partial^2 P^a}{\partial s \partial \theta} \\
& = \frac{1}{r} \frac{\partial}{\partial \theta} ((1 - \kappa r \cos \phi) U^a) \\
& \quad (80)
\end{aligned}$$

Multiplying this expression by  $r\phi_\alpha$  and integrating across section of the duct, we obtain:

$$\begin{aligned}
& \int_0^{2\pi} \int_0^h \frac{\partial W^a}{\partial s} r \psi_\alpha dr d\theta = \int_0^{2\pi} \int_0^h \frac{1}{r} \frac{\partial}{\partial \theta} ((1 - \kappa r \cos \phi) U^a) r \psi_\alpha dr d\theta \\
& LHS := \int_0^{2\pi} \int_0^h \frac{\partial [W_\beta^a \psi_\beta r \psi_\alpha]}{\partial s} dr d\theta - \int_0^{2\pi} \int_0^h \frac{\partial r \psi_\alpha}{\partial s} \psi_\beta dr d\theta W_\beta^a \\
& = \frac{\partial}{\partial s} \int_0^{2\pi} \int_0^h [W_\beta^a \psi_\beta r \psi_\alpha] dr d\theta - \int_0^{2\pi} \frac{dh(s)}{ds} [W_\beta^a \psi_\beta r \psi_\alpha]_0^h d\theta - \int_0^{2\pi} \int_0^h \frac{\partial \psi_\alpha}{\partial s} \psi_\beta r dr d\theta W_\beta^a \\
& = \frac{d}{ds} W_\alpha^a - \int_0^{2\pi} \frac{dh(s)}{ds} [\psi_\beta r \psi_\alpha]_0^h d\theta W_\beta^a - \Psi_{\{\alpha\}\beta}[r] W_\beta^a \\
& RHS := \int_0^{2\pi} \int_0^h \frac{\partial}{\partial \theta} ((1 - \kappa r \cos \phi) U_\beta^a \psi_\beta \psi_\alpha) dr d\theta - \int_0^{2\pi} \int_0^h \frac{\partial (\psi_\alpha)}{\partial \theta} (1 - \kappa r \cos \phi) U_\beta^a \psi_\beta dr d\theta \\
& = 0(\text{periodic}) - \Psi_{(\alpha)\beta}[1 - \kappa r \cos \phi] U_\beta^a
\end{aligned} \tag{81}$$

Thus, LHS=RHS, we have:

$$\underline{\underline{\frac{d}{ds} V_\alpha^a = \int_0^{2\pi} \frac{dh(s)}{ds} [\psi_\beta r \psi_\alpha]_0^h d\theta W_\beta^a + \Psi_{\{\alpha\}\beta}[r] W_\beta^a - \Psi_{(\alpha)\beta}[1 - \kappa r \cos \phi] U_\beta^a}} \tag{82}$$

## D. Substitue pressure modes for transverse velocity modes

### 1. mass equation

$$\begin{aligned}
& \frac{dU_\alpha^a}{ds} - \Psi_{\{\alpha\}\beta}[r] U_\beta^a - ia\kappa \Psi_{\alpha\beta}[r(1 - \kappa \cos(\phi))] P_\beta^a - \Psi_{[\alpha]\beta}[r(1 - \kappa r \cos(\phi))] \underline{\underline{V_\beta^a}} - \Psi_{(\alpha)\beta}[(1 - \kappa r \cos(\phi))] \underline{\underline{W_\beta^a}} \\
& = \Psi_{\alpha\beta\gamma}[r(1 - \kappa r \cos(\phi))] \sum_{b=-\infty}^{+\infty} (-ib\kappa P_\beta^{a-b} P_\gamma^b - ib\kappa U_\beta^{a-b} U_\gamma^b - ib\kappa \underline{\underline{V_\beta^{a-b}}} \underline{\underline{V_\gamma^b}} - ib\kappa \underline{\underline{W_\beta^{a-b}}} \underline{\underline{W_\gamma^b}} - ia\kappa \frac{B}{2A} P_\beta^{a-b} P_\gamma^b)
\end{aligned} \tag{83}$$

Transform:

$$\begin{aligned}
\frac{dU_\alpha^a}{ds} &:= \underline{\underline{I}}u_\alpha^a \\
-\Psi_{\{\alpha\}\beta}[r]U_\beta^a &:= \underline{\underline{-\Psi_{\{\alpha\}\beta}[r]u_\beta^a}} \\
-ia\kappa\Psi_{\alpha\beta}[r(1-\kappa\cos(\phi))]P_\beta^a &:= \underline{\underline{-ia\kappa\Psi_{\alpha\beta}[r(1-\kappa\cos(\phi))]p_\beta^a}} \\
-\Psi_{[\alpha]\beta}[r(1-\kappa\cos(\phi))]V_\beta^a &:= \underline{\underline{-\Psi_{[\alpha]\delta}[r(1-\kappa\cos(\phi))]V_{\delta\beta}^a}} \\
-\Psi_{(\alpha)\beta}[(1-\kappa\cos(\phi))]W_\beta^a &:= \underline{\underline{-\Psi_{(\alpha)\delta}[(1-\kappa\cos(\phi))]W_{\delta\beta}^a}} \\
\Psi_{\alpha\beta\gamma}[r(1-\kappa\cos(\phi))] \sum_{b=-\infty}^{+\infty} (-ib\kappa P_\beta^{a-b}P_\gamma^b) &:= \sum_{b=-\infty}^{+\infty} -ib\kappa \sum_{\beta=0}^{+\infty} \sum_{\gamma=0}^{+\infty} \underline{\underline{\Psi_{\alpha\beta\gamma}[(1-\kappa\cos(\phi))]p_\beta^{a-b}p_\gamma^b}} = (B_1[p,p])_\alpha^a \\
\Psi_{\alpha\beta\gamma}[r(1-\kappa\cos(\phi))] \sum_{b=-\infty}^{+\infty} (-ib\kappa U_\beta^{a-b}U_\gamma^b) &:= \sum_{b=-\infty}^{+\infty} -ib\kappa \sum_{\beta=0}^{+\infty} \sum_{\gamma=0}^{+\infty} \underline{\underline{\Psi_{\alpha\beta\gamma}[(1-\kappa\cos(\phi))]u_\beta^{a-b}u_\gamma^b}} = (A_1[u,u])_\alpha^a \\
\Psi_{\alpha\beta\gamma}[r(1-\kappa\cos(\phi))] \sum_{b=-\infty}^{+\infty} (-ib\kappa V_\beta^{a-b}V_\gamma^b) &:= \sum_{b=-\infty}^{+\infty} -ib\kappa \sum_{\beta=0}^{+\infty} \sum_{\gamma=0}^{+\infty} \sum_{\delta,\epsilon=0}^{\infty} \underline{\underline{\Psi_{\alpha\delta\epsilon}[r(1-\kappa\cos(\phi))]V_{\delta\beta}^{a-b}V_{\epsilon\gamma}^b p_\beta^{a-b}p_\gamma^b}} \\
\Psi_{\alpha\beta\gamma}[r(1-\kappa\cos(\phi))] \sum_{b=-\infty}^{+\infty} (-ib\kappa W_\beta^{a-b}W_\gamma^b) &:= \sum_{b=-\infty}^{+\infty} -ib\kappa \sum_{\beta=0}^{+\infty} \sum_{\gamma=0}^{+\infty} \sum_{\delta,\epsilon=0}^{\infty} \underline{\underline{\Psi_{\alpha\delta\epsilon}[r(1-\kappa\cos(\phi))]W_{\delta\beta}^{a-b}W_{\epsilon\gamma}^b p_\beta^{a-b}p_\gamma^b}} \\
\Psi_{\alpha\beta\gamma}[r(1-\kappa\cos(\phi))] \sum_{b=-\infty}^{+\infty} (-ia\kappa \frac{B}{2A} P_\beta^{a-b}P_\gamma^b) &:= \sum_{b=-\infty}^{+\infty} -ia\kappa \frac{B}{2A} \sum_{\beta=0}^{+\infty} \sum_{\gamma=0}^{+\infty} \underline{\underline{\Psi_{\alpha\beta\gamma}[(1-\kappa\cos(\phi))]p_\beta^{a-b}p_\gamma^b}}
\end{aligned} \tag{84}$$

$$\begin{aligned}
&\frac{d}{ds}P_\alpha^a - ia\kappa\Psi_{\alpha\beta}[r(1-\kappa\cos\phi)]U_\beta^a - \int_0^{2\pi} hh'[\psi_\beta\psi_\alpha]_{r=h}d\theta P_\beta^a - \Psi_{\{\alpha\}\beta}[r]P_\beta^a \\
&= \sum_{b=-\infty}^{+\infty} \underline{\underline{term\mathcal{D}1}} : \Psi_{\{\alpha\}\beta\gamma}[r]U_\beta^{a-b}U_\gamma^a + \Psi_{[\alpha]\beta\gamma}[r(1-\kappa\cos\phi)]V_\beta^{a-b}U_\gamma^a + \Psi_{(\alpha)\beta\gamma}[(1-\kappa\cos\phi)]W_\beta^{a-b}U_\gamma^a \\
&\quad + \underline{\underline{term(D1+\mathcal{P}1)}} : i(a)\kappa\Psi_{\alpha\beta\gamma}[r(1-\kappa\cos\phi)]P_\beta^{a-b}U_\gamma^b \\
&\quad + \underline{\underline{term\mathcal{D}1}} : -\frac{\partial}{\partial s}(\Psi_{\alpha\beta\gamma}[r])U_\beta^{a-b}U_\gamma^b - \Psi_{\alpha\beta\gamma}[r](\frac{dU_\beta^{a-b}}{ds}U_\gamma^b + \frac{dU_\gamma^b}{ds}U_\beta^{a-b}) \\
&\quad + \underline{\underline{term\mathcal{X}1}} : \Psi_{\alpha\beta\gamma}[r\cos\phi]U_\beta^{a-b}\underline{\underline{V_\gamma^b}} - \kappa\Psi_{\alpha\beta\gamma}[r\sin\phi]U_\beta^{a-b}\underline{\underline{W_\gamma^b}}
\end{aligned} \tag{85}$$

Transform:

$$\begin{aligned}
& \frac{d}{ds} P_\alpha^a := \underline{I} p'_\alpha^a \\
& -ia\kappa \Psi_{\alpha\beta}[r(1 - \kappa r \cos\phi)] U_\beta^a := -ia\kappa \Psi_{\alpha\beta}[r(1 - \kappa \cos(\phi))] u_\beta^a \\
& - \int_0^{2\pi} hh'[\psi_\beta \psi_\alpha]_{r=h} d\theta P_\beta^a - \Psi_{\{\alpha\}\beta}[r] P_\beta^a := - \int_0^{2\pi} hh'[\psi_\beta \psi_\alpha]_{r=h} d\theta p_\beta^a - \underline{\Psi_{\{\alpha\}\beta}[r] p_\beta^a} \\
& \Psi_{\{\alpha\}\beta\gamma}[r] \sum_{b=-\infty}^{+\infty} U_\beta^{a-b} U_\gamma^a := \sum_{b=-\infty}^{+\infty} \sum_{\beta=0}^{+\infty} \sum_{\gamma=0}^{+\infty} \underline{\Psi_{\{\alpha\}\beta\gamma}[r] u_\beta^{a-b} u_\gamma^b} \\
& \Psi_{[\alpha]\beta\gamma}[r(1 - \kappa r \cos\phi)] \sum_{b=-\infty}^{+\infty} \underline{V_\beta^{a-b} U_\gamma^a} := \sum_{b=-\infty}^{+\infty} \sum_{\beta=0}^{+\infty} \sum_{\gamma=0}^{+\infty} \sum_{\delta,\epsilon=0}^{\infty} \underline{\Psi_{[\alpha]\delta\epsilon}[r(1 - \kappa r \cos\phi)] \mathbf{V}_{\delta\beta}^{a-b} \mathbf{I}_{\epsilon\gamma}^b p_\beta^{a-b} u_\gamma^b} \\
& \Psi_{(\alpha)\beta\gamma}[(1 - \kappa r \cos\phi)] \sum_{b=-\infty}^{+\infty} \underline{W_\beta^{a-b} U_\gamma^a} := \sum_{b=-\infty}^{+\infty} \sum_{\beta=0}^{+\infty} \sum_{\gamma=0}^{+\infty} \sum_{\delta,\epsilon=0}^{\infty} \underline{\Psi_{(\alpha)\delta\epsilon}[(1 - \kappa r \cos\phi)] \mathbf{W}_{\delta\beta}^{a-b} \mathbf{I}_{\epsilon\gamma}^b p_\beta^{a-b} u_\gamma^b} \\
& ia\kappa \Psi_{\alpha\beta\gamma}[r(1 - \kappa r \cos\phi)] \sum_{b=-\infty}^{+\infty} P_\beta^{a-b} U_\gamma^b := ia\kappa \sum_{b=-\infty}^{+\infty} \sum_{\beta=0}^{+\infty} \sum_{\gamma=0}^{+\infty} \underline{\Psi_{\alpha\beta\gamma}[r(1 - \kappa r \cos\phi)] p_\beta^{a-b} u_\gamma^b} \\
& - \frac{\partial}{\partial s} (\Psi_{\alpha\beta\gamma}[r]) \sum_{b=-\infty}^{+\infty} U_\beta^{a-b} U_\gamma^b := \sum_{b=-\infty}^{+\infty} \sum_{\beta=0}^{+\infty} \sum_{\gamma=0}^{+\infty} - \frac{\partial}{\partial s} (\Psi_{\alpha\beta\gamma}[r]) u_\beta^{a-b} u_\gamma^b \\
& - \Psi_{\alpha\beta\gamma}[r] \sum_{b=-\infty}^{+\infty} \left( \frac{dU_\beta^{a-b}}{ds} U_\gamma^b + \frac{dU_\gamma^b}{ds} U_\beta^{a-b} \right) := \sum_{b=-\infty}^{+\infty} (\Psi_{\alpha\beta\gamma}[r][G, I] + \Psi_{\alpha\beta\gamma}[r][I, G]) u_\beta^{a-b} u_\gamma^b \\
& \Psi_{\alpha\beta\gamma}[r \cos\phi] U_\beta^{a-b} \underline{V_\gamma^b} - \kappa \Psi_{\alpha\beta\gamma}[r \sin\phi] U_\beta^{a-b} \underline{W_\gamma^b} := \sum_{b=-\infty}^{+\infty} \Psi_{\alpha\beta\gamma}[r \cos\phi][I, V] - \kappa \Psi_{\alpha\beta\gamma}[r \sin\phi][I, W] u_\gamma^b
\end{aligned} \tag{86}$$

$$\begin{aligned}
& -ia\kappa \Psi_{\alpha\beta}[r(1 - \kappa r \cos\phi)] V_\beta^a \\
& + \int_0^{2\pi} [\psi_\alpha \psi_\beta r(1 - \kappa r \cos\phi)]_0^h d\theta P_\beta^a - \Psi_{[\alpha]\beta}[r(1 - \kappa r \cos\phi)] P_\beta^a - \Psi_{\alpha\beta}[1 - 2\kappa r \cos\phi] P_\beta^a \\
& = \underline{termD2} : \Psi_{\{\alpha\}\beta\gamma}[r] U_\beta^{a-b} V_\gamma^a + \Psi_{[\alpha]\beta\gamma}[r(1 - \kappa r \cos\phi)] V_\beta^{a-b} V_\gamma^a + \Psi_{(\alpha)\beta\gamma}[(1 - \kappa r \cos\phi)] W_\beta^{a-b} V_\gamma^a \\
& \quad + \underline{term(D2 + P2)} : i(a)\kappa \Psi_{\alpha\beta\gamma}[r(1 - \kappa r \cos\phi)] P_\beta^{a-b} V_\gamma^b \\
& \quad + \underline{termD2} : - \frac{\partial}{\partial s} (\Psi_{\alpha\beta\gamma}[r] U_\beta^{a-b} U_\gamma^b - \Psi_{\alpha\beta\gamma}[r] \left( \frac{dU_\beta^{a-b}}{ds} V_\gamma^b + \frac{dV_\gamma^b}{ds} U_\beta^{a-b} \right)) \\
& \quad + \underline{termX2} : \Psi_{\alpha\beta\gamma}[1 - \kappa r \cos\phi] W_\beta^{a-b} W_\gamma^b - \kappa \Psi_{\alpha\beta\gamma}[r \cos\phi] U_\beta^{a-b} U_\gamma^b
\end{aligned} \tag{87}$$

$$\begin{aligned}
& -ia\kappa\Psi_{\alpha\beta}[r(1-\kappa r\cos\phi)]W_{\beta}^a \\
& -\Psi_{(\alpha)\beta}[(1-\kappa r\cos\phi)]P_{\beta}^a - \kappa\Psi_{\alpha\beta}[r\sin\phi]P_{\beta}^a \\
= & \underline{term\mathcal{D}2}:\Psi_{\{\alpha\}\beta\gamma}[r]U_{\beta}^{a-b}W_{\gamma}^a + \Psi_{[\alpha]\beta\gamma}[r(1-\kappa r\cos\phi)]V_{\beta}^{a-b}W_{\gamma}^a + \Psi_{(\alpha)\beta\gamma}[(1-\kappa r\cos\phi)]W_{\beta}^{a-b}W_{\gamma}^a \\
& +\underline{term(D2+\mathcal{P}2)}:i(a)\kappa\Psi_{\alpha\beta\gamma}[r(1-\kappa r\cos\phi)]P_{\beta}^{a-b}W_{\gamma}^b \\
& +\underline{term\mathcal{D}2}:-\frac{\partial}{\partial s}(\Psi_{\alpha\beta\gamma}[r]U_{\beta}^{a-b}V_{\gamma}^b - \Psi_{\alpha\beta\gamma}[r](\frac{dU_{\beta}^{a-b}}{ds}W_{\gamma}^b + \frac{dW_{\gamma}^b}{ds}U_{\beta}^{a-b})) \\
& +\underline{term\mathcal{X}2}:\kappa\Psi_{\alpha\beta\gamma}[r\sin\phi]U_{\beta}^{a-b}U_{\gamma}^b - \Psi_{\alpha\beta\gamma}[1-\kappa r\cos\phi]W_{\beta}^{a-b}V_{\gamma}^b
\end{aligned} \tag{88}$$

## V. Tensors in matlab for numerical simulation

### A. Tensor times vectors: $\mathcal{A}\bar{\times}_n u$

Let  $\mathcal{A}$  be a tensor of size  $I_1 \times I_2 \times \dots \times I_N$ ,  $u$  be a vector of size  $I_n$ .

We have:

$$\begin{aligned}
ttv(\mathcal{A}, \{u\}, [n]) &= (\mathcal{A}\bar{\times}_n u)(i_1, \dots, i_{n-1}, i_{n+1}, \dots, i_N) \\
&= \sum_{i_n=1}^{I_n} \mathcal{A}(i_1, i_2, \dots, i_N)u(i_n)
\end{aligned} \tag{89}$$

$$\begin{aligned}
ttv(A_{m \times n}, \{u_{m \times 1}\}, [1]) &= A_{m \times n} \bar{\times}_1 u_{m \times 1} = A_{m \times n}^T u_{m \times 1} \\
ttv(A_{m \times n}, \{v_{n \times 1}\}, [2]) &= A_{m \times n} \bar{\times}_2 v_{n \times 1} = A_{m \times n} v_{n \times 1}
\end{aligned} \tag{90}$$

Property:

$$\begin{aligned}
ttv(\mathcal{A}, \{u, v\}, [m, n]) &= \mathcal{A}\bar{\times}_m u \bar{\times}_n v \\
= ttv(ttv(\mathcal{A}, \{u\}, [m]), \{v\}, [n-1]) &= (\mathcal{A}\bar{\times}_m u) \bar{\times}_{n-1} v \\
= ttv(ttv(\mathcal{A}, \{v\}, [n]), \{u\}, [m]) &= (\mathcal{A}\bar{\times}_n v) \bar{\times}_m u
\end{aligned} \tag{91}$$

Multiplication with a sequence of vectors

$$\beta = \mathcal{A}\bar{\times}_1 u^{(1)} \bar{\times}_2 u^{(2)} \dots \bar{\times}_N u^{(N)} = \mathcal{A}\bar{\times} u \tag{92}$$

$$like : ttv(X, \{A, B, C, D\}) = ttv(X, \{A, B, C, D\}, [1234]) = ttv(X, \{D, C, B, A\}, [4321])$$



Multiplication with **all but one** of a sequence of vectors

$$b = \mathcal{A} \bar{\times}_1 u^{(1)} \bar{\times}_2 u^{(2)} \dots \bar{\times}_{n-1} u^{(2)} \bar{\times}_{n+1} u^{(2)} \dots \bar{\times}_N u^{(N)} = \mathcal{A} \bar{\times}_{-n} u$$

$$like : X = tenrand([5, 3, 4, 2]);$$
(93)

$$A = rand(5, 1); B = rand(3, 1); C = rand(4, 1); D = rand(2, 1);$$

$$Y = ttv(X, \{A, B, D\}, -3) = ttv(X, \{A, B, C, D\}, -3)$$

**B. Tensor times matrix (ttm):  $\mathcal{A} \times_n u$**

Let  $\mathcal{A}$  be a tensor of size  $I_1 \times I_2 \times \dots \times I_N$ ,  $U$  be a matrix of size  $J_n \times I_n$ .

We have:

$$ttm(\mathcal{A}, \{U\}, [n]) = (\mathcal{A} \times_n U)(i_1, \dots, i_{n-1}, j_n, i_{n+1}, \dots, i_N)$$

$$\sum_{i_n=1}^{I_n} \mathcal{A}(i_1, i_2, \dots, i_N) U(j_n, i_n)$$
(94)

$$like : X = tensor(rand(5, 3, 4, 2)); A = rand(4, 5);$$

$$Y = ttm(X, A, 1) = ttm(X, \{A, B, C, D\}, 1) = ttm(X, A', 1, 't')$$

Matrix Interpretation

$$ttm(A_{m \times n}, \{U_{m \times k}^T\}, [1]) = A \times_1 U^T = U^T A$$

$$ttm(A_{m \times n}, \{V_{m \times k}^T\}, [2]) = A \times_2 V^T = AV$$
(95)

$$ttm(A, \{U, V\}, [1, 2]) = UAV^T$$

$$Y = ttm(X, A, B, C, D, [1234]); \% < - - 4 - waymutlply.$$

$$Y = ttm(X, D, C, B, A, [4321]); \% < - - Sameasabove.$$

$$Y = ttm(X, A, B, C, D); \% < - - Sameasabove.$$

$$Y = ttm(X, A', B', C', D', 't'); \% < - - Sameasabove.$$

$$Y = ttm(X, C, D, [34]); \% < - - XtimesCinmode - 3Dinmode - 4 \quad (96)$$

$$Y = ttm(X, A, B, C, D, [34]); \% < - - Sameasabove.$$

$$Y = ttm(X, A, B, D, [124]); \% < - - 3 - waymultiply.$$

$$Y = ttm(X, A, B, C, D, [124]); \% < - - Sameasabove.$$

$$Y = ttm(X, A, B, D, -3); \% < - - Sameasabove.$$

$$Y = ttm(X, A, B, C, D, -3); \% < - - Sameasabove.$$

Property

$$\begin{aligned} ttm(\mathcal{A}, \{u, v\}, [m, n]) &= \mathcal{A} \times_m u \bar{\times}_n v \\ &= ttm(ttm(\mathcal{A}, \{u\}, [m]), \{v\}, [n]) = (\mathcal{A} \times_m u) \times_n v \\ &= ttm(ttm(\mathcal{A}, \{v\}, [n]), \{u\}, [m]) = (\mathcal{A} \times_n v) \times_m u \end{aligned} \quad (97)$$

### C. Tensor times tensor (ttt): $\langle \mathcal{A}, \mathcal{B} \rangle$

Let  $\mathcal{A}$  and  $\mathcal{B}$  be a tensor of size  $I_1 \times I_2 \times \dots \times I_N$ .

$$\begin{aligned} \langle \mathcal{A}, \mathcal{B} \rangle &= \\ \beta &= \sum_{i_1=1}^{I_1} \sum_{i_2=1}^{I_2} \dots \sum_{i_N=1}^{I_N} \mathcal{A}(i_1, i_2, \dots, i_N) \mathcal{B}(i_1, i_2, \dots, i_N) \end{aligned} \quad (98)$$

$X = \text{tensor}(\text{rand}(4, 2, 3)); Y = \text{tensor}(\text{rand}(3, 4, 2));$

$Z = \text{ttt}(X, Y); \% < - - \text{Outerproduct of } X \text{ and } Y.$

$\text{size}(Z)$

$Z = \text{ttt}(X, X, 1 : 3) \% < - - \text{Innerproduct of } X \text{ with itself.}$

(99)

$Z = \text{ttt}(X, Y, [123], [231]) \% < - - \text{Innerproduct of } XY.$

$Z = \text{innerprod}(X, \text{permute}(Y, [231])) \% < - - \text{Same as above.}$

$Z = \text{ttt}(X, Y, [13], [21]) \% < - - \text{Product of } XY \text{ along specified dims.}$