Fourier Methods for Turbomachinery

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‘Turbomachinery’ & ‘CFD’ in Turbomachinery CFD ?

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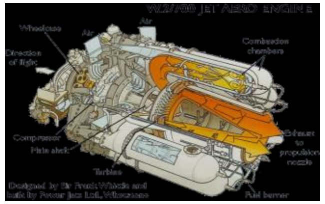
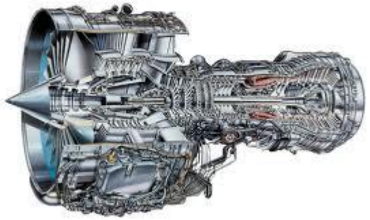
1941 → Jet Engine

1940s (Whittle’s) *(No CFD!)*



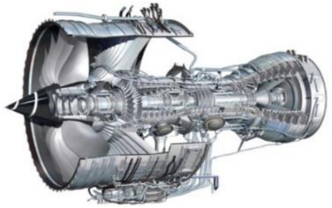
1975 → *Turbo CFD (Denton’s)*

1970s *(bit CFD)*

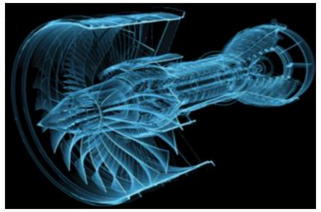


1990s *(more CFD)*

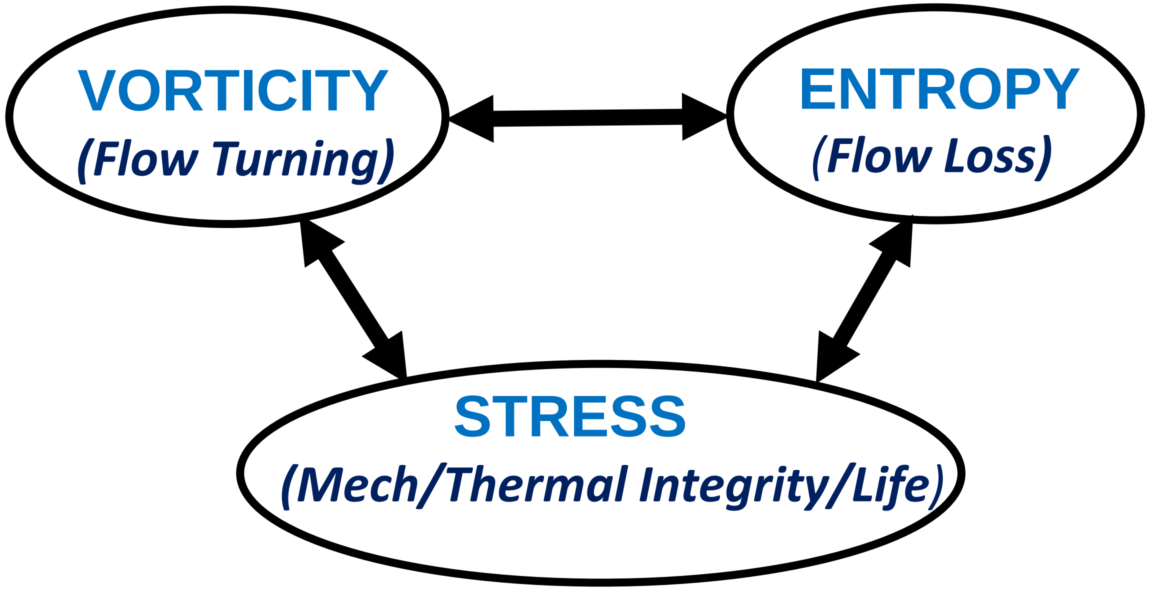
2000s *(lots CFD!)*



2020s (AI - CFD?)



- Basic Turbo Design Drivers: ***What Make It Work & Live?***



‘Turbo Δ’

- Multi-physics, M-disciplinary & M-component Interactive Settings

  ➔ *Dictate how CFD methods are applied to Turbomachinery*

  but also:

  ➔ *Influence how Turbo-CFD methods may be developed*.

Outline

- **Background & Motivation**
  - *Historical bits of 'Turbomachinery' in 'Turbomachinery CFD' (1975 - 1990)*
  - *Motivating Context & Brief Account of 'Turbo Fourier Methods' (1990 -)*

- **Time-Domain Methods** *('Spatial Truncation')*
  - *Temporal Fourier Method: Multiple passages* ➔ *Single-passage ('Phase-shift periodicity')*
  - *Multi-disturbance Method: single-passage/row in multi-rows*
  - *Spatial Fourier Method: Discrete Small Blocks for Whole Domain ('Block-spectral' model)*

- **Frequency-Domain Methods** *('Temporal Truncation')*
  - *Nonlinear Harmonic Model*
  - *Time-spectral Model ('Harmonic Balance')*
  - *Multi-stage (Rotor-Stator + Rotor-Rotor/Stator-Stator) Interactions*

Some Milestones in Turbomachinery CFD
- from Single Bladerow to Multi-rows/stages

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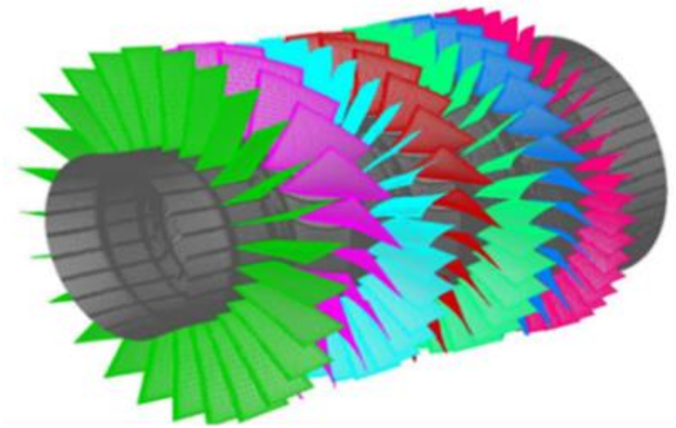
John Denton (1975) - marking the start of Turbo CFD

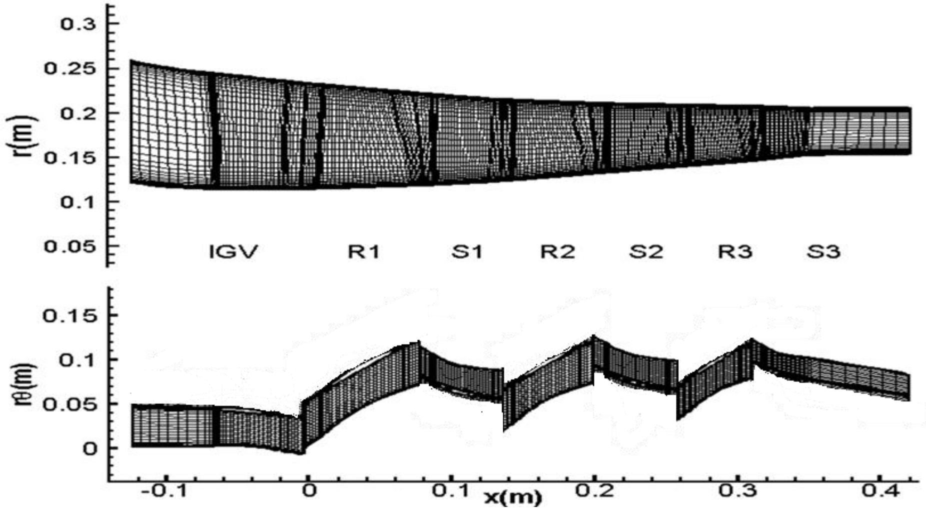
Full 3D Euler (Single blade-passage, Single blade-row, Steady Flow)

John Denton (1979)

'Mixing-plane' for Multi-Stage Interaction ***(Single-passage/row, Steady Flow)***

-the WORKHORSE in designing all WORKING turbomachines (Air, Land & Sea)





Multirow/stage Interaction:

- *'Well designed/analysed' parts in isolation do not work well (when put together)!*
- *Power of the overall conservation (even with all missing/wrong details…!)*

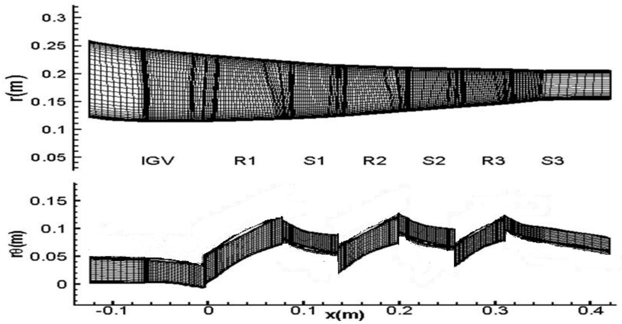
'Average Passage' Model: Informative Framework

<u>John Adamczyk</u> (NASA, 1985)

'Average-passage' for Rotor-Stator Coupling

- Single-passage/row,

- Averaging ➔ An <u>Open</u> system needing <u>Closure</u>



- **Averaging ➔ Challenges and Opportunities**
  Reynolds-Averaging ➔ 'Reynolds Stress' *- hard jobs for many turbulence modelers/profs...*
  Passage-Averaging ➔ 'Deterministic Stress' *- easier (?) jobs for a few turbo aerodynamists...*

➔ **Impetus for developing less-empirical & more efficient ways to close 'Deterministic Stresses'**
-Closing Them by Computing Them (Efficiently) ?

'Shared' Challenge (& Motivation) for Both Aerodynamics and Aeroelasticity

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- **More General Challenge:**

Aerodynamics: moving from RANS to URANS (just Time-marching in 'τ' ➔ Time-marching in 't' ?)

Single Passage Steady ➔ Multi-passage/Whole annulus Unsteady

Extra cost ~O(10^3) : ~O(10) from Steady to Unsteady; ~O(10^2) from 1 passage to whole annulus

Aeroelasticity: moving from Linear (Linearised based on RANS) to Nonlinear (URANS)

Single Passage 'Steady' (Harmonic) ➔ Multi-passage/Whole annulus Unsteady

Extra cost ~O(10^3)

- **More General Motivation for Fourier Methods**

- Much Faster (by ~O(10^2)) Nonlinear Method than Conventional Mutli-passage URANS.
- Primarily by significant circumferential truncation (to Single-passage or the like)

Some Shared Basics: ***‘Phase-Shift’ Periodicity*** *for Both Aerodynamics & Aeroelasticity*

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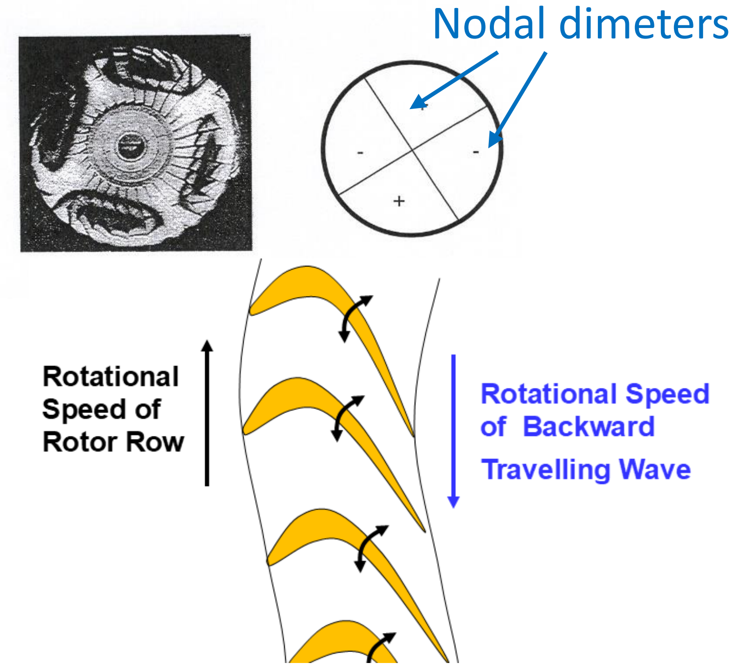
- **Blade Flutter/Forced Response**



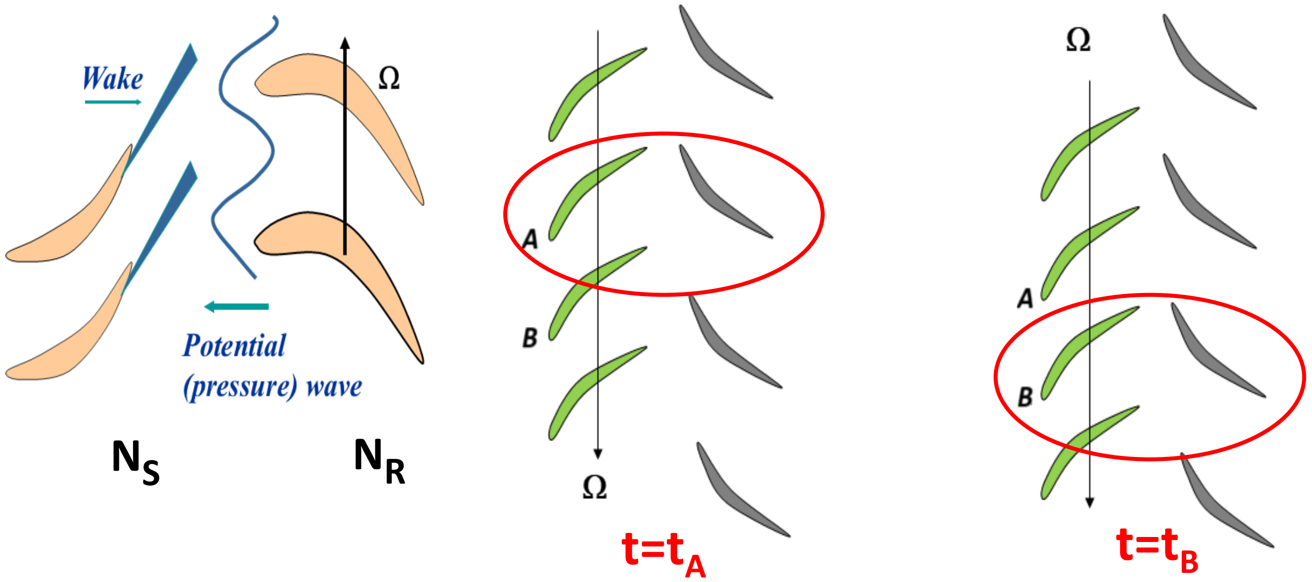
Inter-Blade Phase Angle (IBPA)

$$\sigma = \pm\frac{2\pi n}{N_b} \qquad (n = 1, 2, .., N_b/2)$$

N_b – number of blades (blade row to be modelled)

n – number of nodal diameters (structural mode)

- **Stator-Rotor Interaction**



Inter-Blade Phase Angle (IBPA)

$$\sigma = \frac{2\pi N_S}{N_R}$$

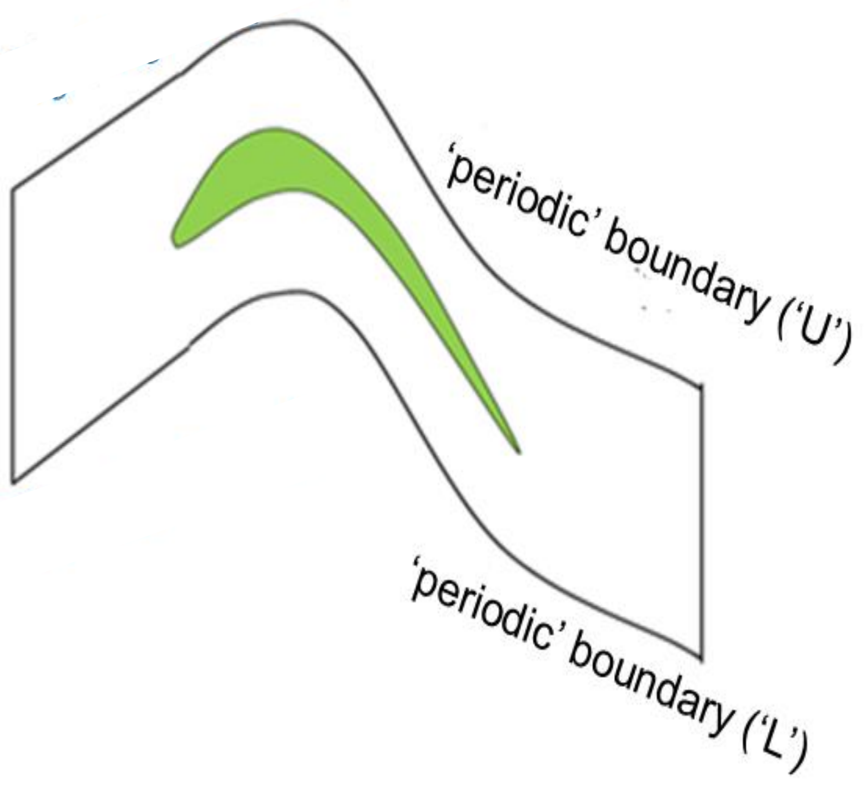
N_R– number of rotor blades (bladerow to be modelled)

N_S– number of stator blades (bladerow of disturbances)

Time-Domain Single-passage Solution: 'Fourier Shape Correction' *(He,1990)*

- **Fourier Spectrum to enforce 'Phase-shift' Periodicity for Nonlinear Time-marching Solutions**
  (*'Tangible target': can run low frequency flutter cases without memory limited by 'Direct Store', Erdos et al 1977)*

***Disturbance** (Flutter/Distortion)*

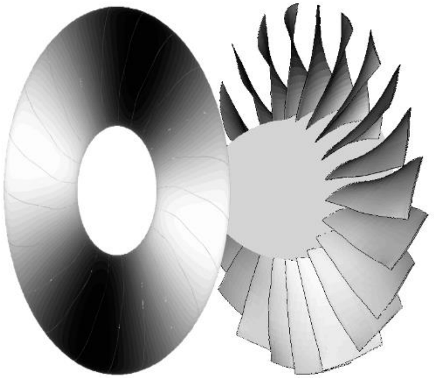


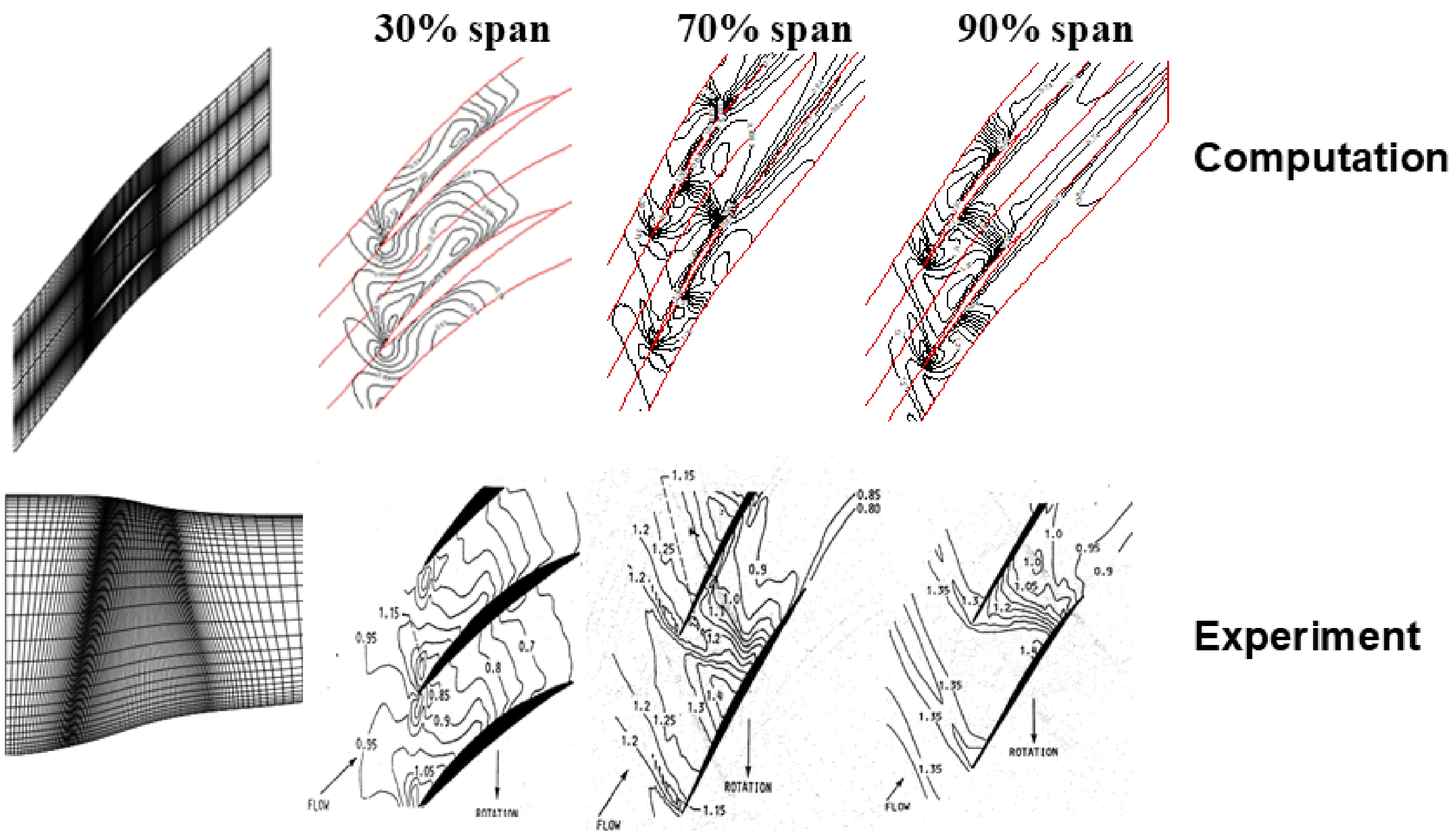
Single-passage Domain
(Flutter/Forced Response)

- **SHAPE** in time by Fourier Transfer at 'periodic' boundaries.
- **CORRECT** the current solution by updating Fourier coefficients accordingly.
- When periodically converged (***'Phase-shift Periodicity'*** satisfied):

$$\bar{U}_U = \bar{U}_L, \quad A_U = A_L, \quad \varphi_U = \sigma\,(IBPA)$$

NASA Rotor-67 under Inlet Distortion *(Li & He 2002)*





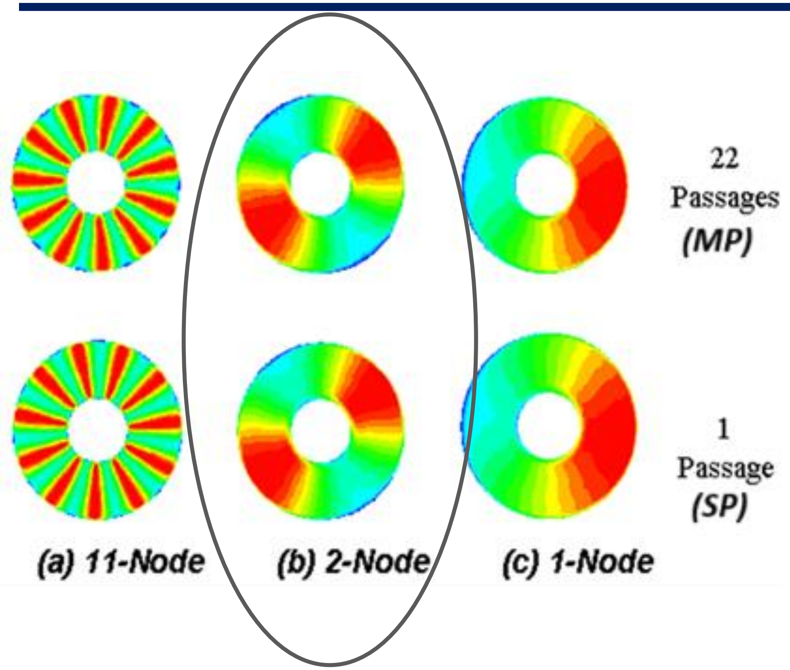
(a) Mesh

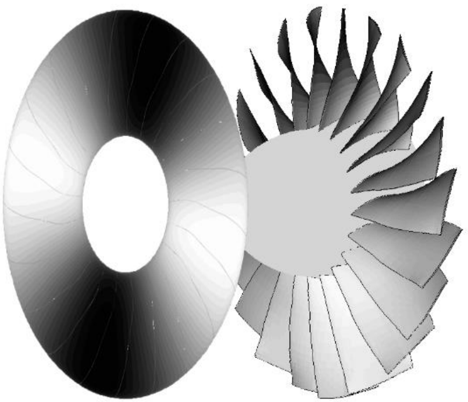
(b) Relative Mach Number Compared with Exp Data

Steady Flow (Clean Inlet) Validation

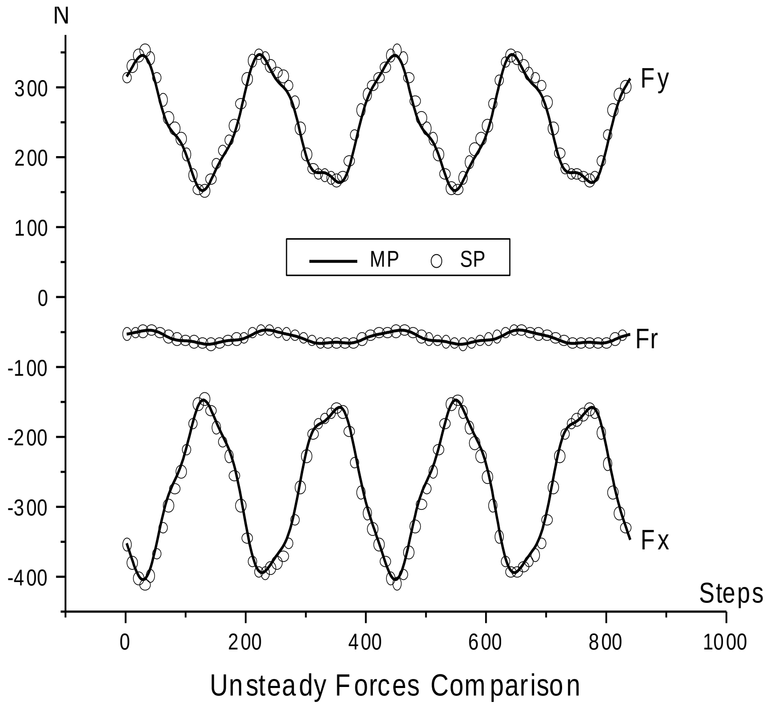
NASA Rotor-67 under Two Nodes Distortion *(Li & He 2002)*

(Q: Fourier Transform is seemingly a linear operator, how can it model nonlinear flow?)



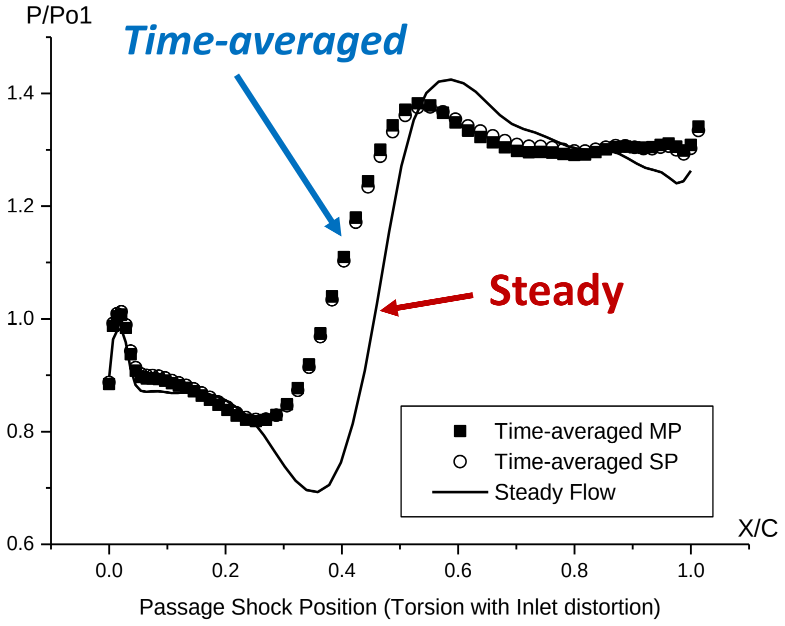


Unsteady



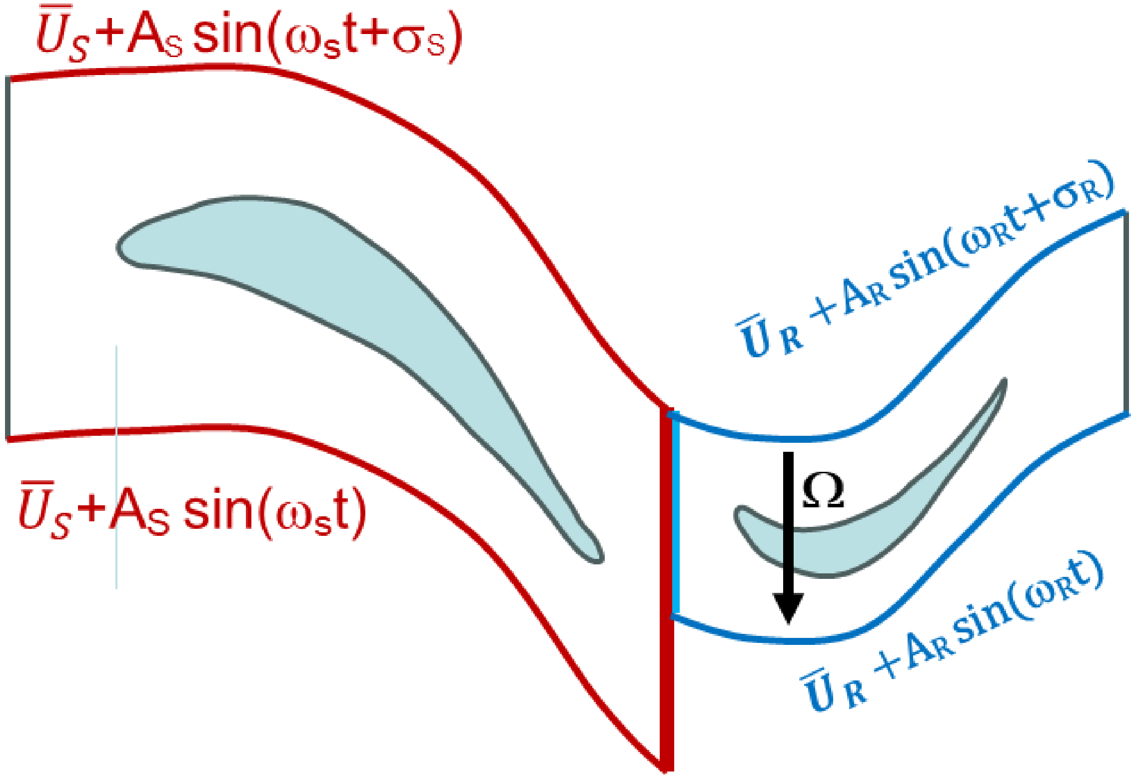
Time Traces of Blade Forces

'Steady'

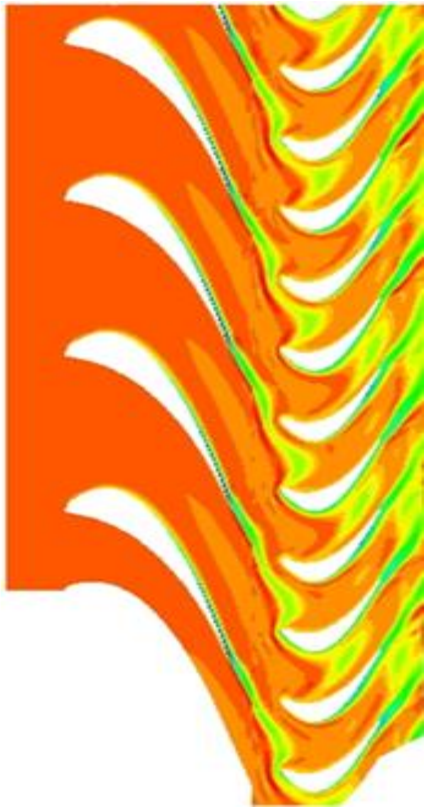


Time-Averaged Surface Pressures

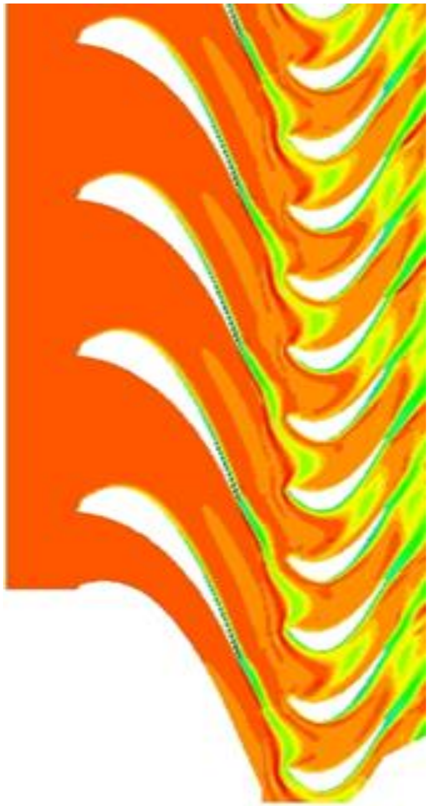
Stage Configurations *(Dewhurst & He 2000, Li and He 2002)*



Stator-Rotor (Bladerow Interaction)



Single-passage Solution
('Phase-shift' reconstructed)



Multi-passage Solution
(Directly solved)

Towards *Multiple Disturbances* Settings: *Accounting for 'Reflections'*

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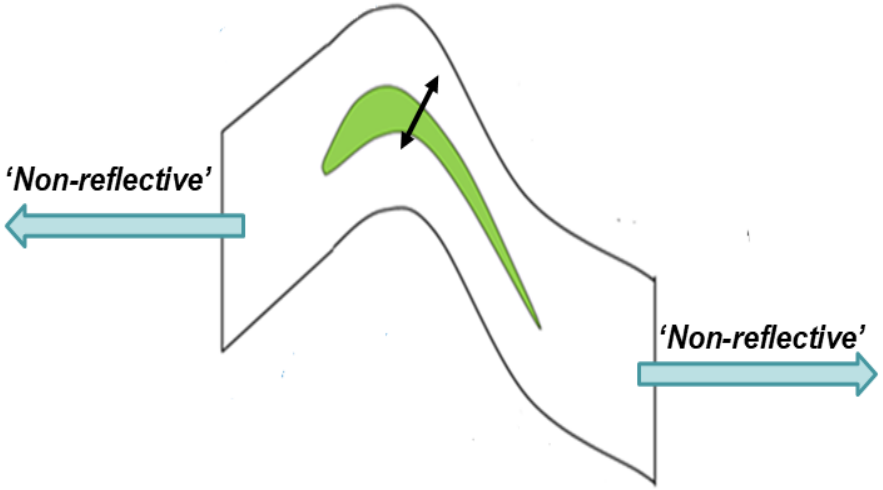
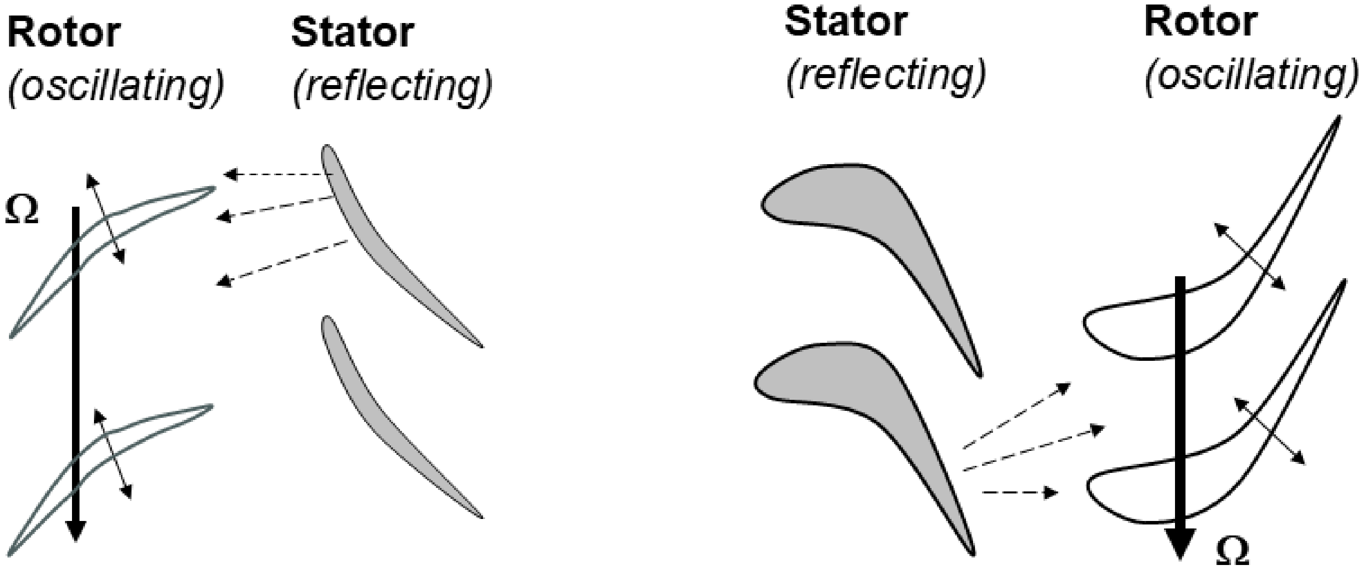
Idealised Oscillating Bladerow

('Tunned Cascade' in Infinite Long Duct)



Oscillating Rotor Blades in Realistic Setting

(He, Cambridge Turbomachinery Course, 2008)



a) Frontal Fan/Compressor Stage

b) Rear Turbine Stage

➔ *Single-passage subject to multiples disturbances ?*

General Fourier Model for Multiple Disturbances
('Generalised Shape-Correction', He 1992)

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- General form: $\mathbf{N_{dist}}$ disturbances (each with *a primary frequency)*:

$$\boldsymbol{U}(\boldsymbol{x},\boldsymbol{t}) = \overline{\boldsymbol{U}} + \sum_{\boldsymbol{i}=1}^{\boldsymbol{N_{dist}}} \boldsymbol{U_i}(\boldsymbol{x},\boldsymbol{t})$$

- Each with its own primary frequency ω_i (i=1,2,…. N_{dist}) modelled by its own Fourier spectrum:

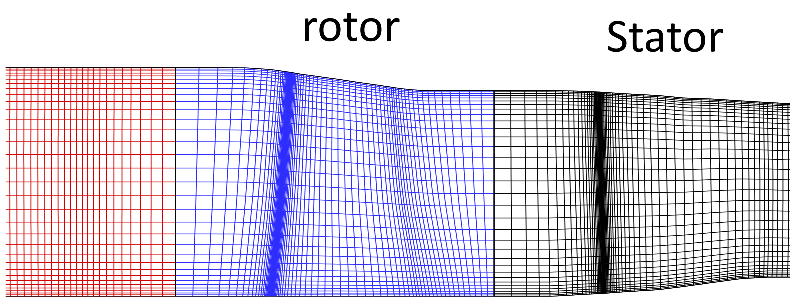
$$\boldsymbol{U_i} = \sum_{\boldsymbol{n}=1}^{\boldsymbol{N_f}} \left[\boldsymbol{A_{n_i}} \cos(\boldsymbol{n\omega_i t}) + \mathbf{B}_{\boldsymbol{n_i}} \sin(\boldsymbol{n\omega_i t})\right], \quad (\boldsymbol{i} = 1, 2, \ldots \boldsymbol{N_{dist}})$$

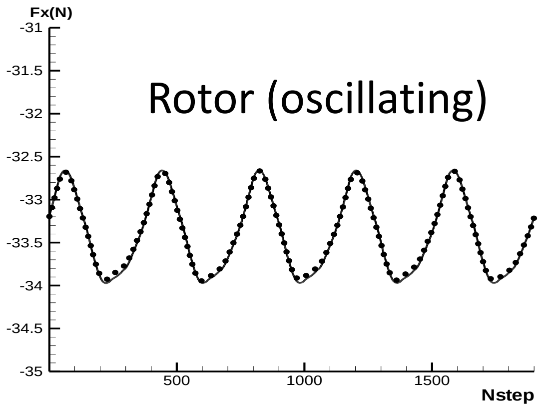
- Remarks on the basis:
  i) All Disturbances are linearly superimposable ('orthogonal' like all Fourier modes).
  ii) Nonlinear cross-coupling among disturbances & the time-mean included (like all Fourier harmonics)

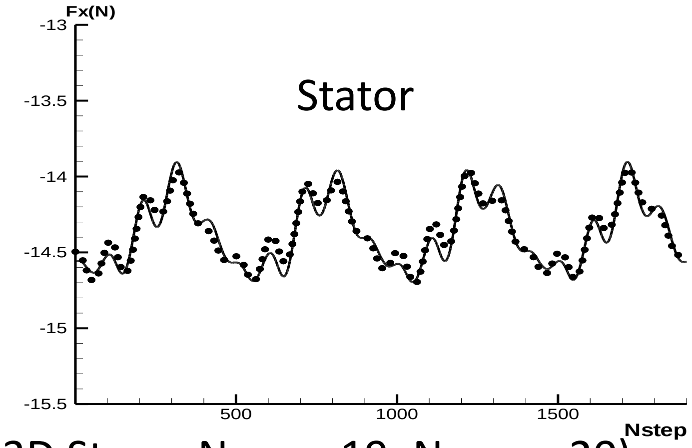
- Implementation:
  i) Straightforward Fourier transform needs all disturbances to beat –impractical (almost impossible for some)
  ii) An Effective Mitigation Enabler: *'**Partial Substitution**'* in updating Fourier-coefficients *(He, 1992).*

Blade Aeroelastic Stability of Embedded Rotor (Lyon Transonic Compressor)

-Blade numbers: 33 (IGV), 57 (rotor), 58 (stator), *(Li & He 2005)*



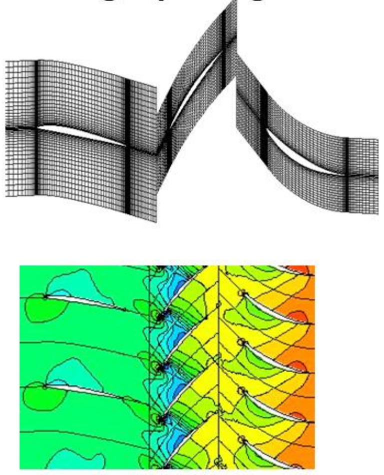




Unsteady Forces: **MP** *vs* **SP** (3D Stage: N_{rotor}=19, N_{stator}=20)

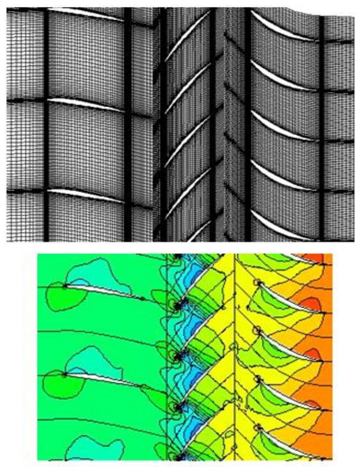
Gaping Analysis for 3-rows *(midspan section)*

Single-passage

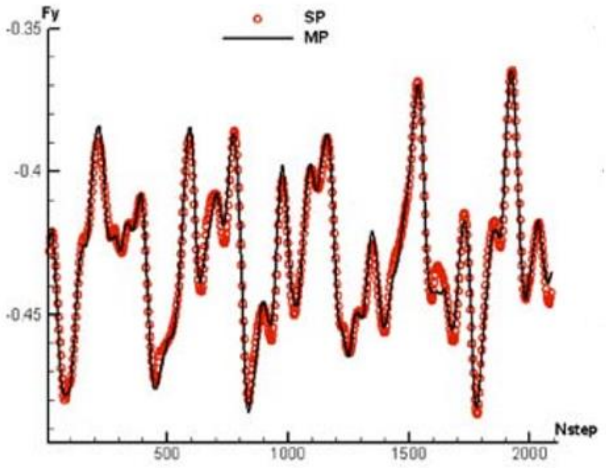


Pressure ***(reconstructed)***

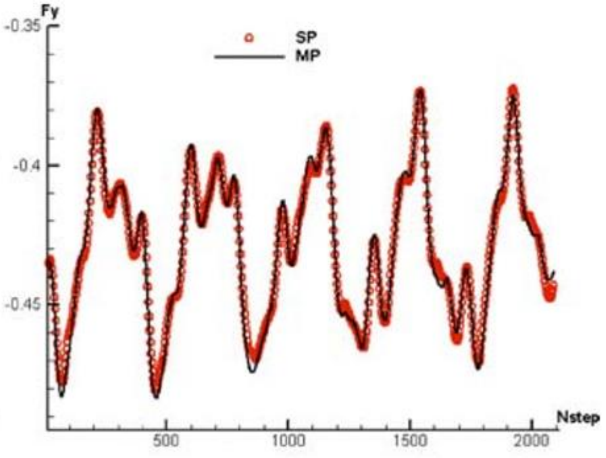
Multi-passages



Pressure ***(direct solution)***



(a) 30% Intra-row Gap

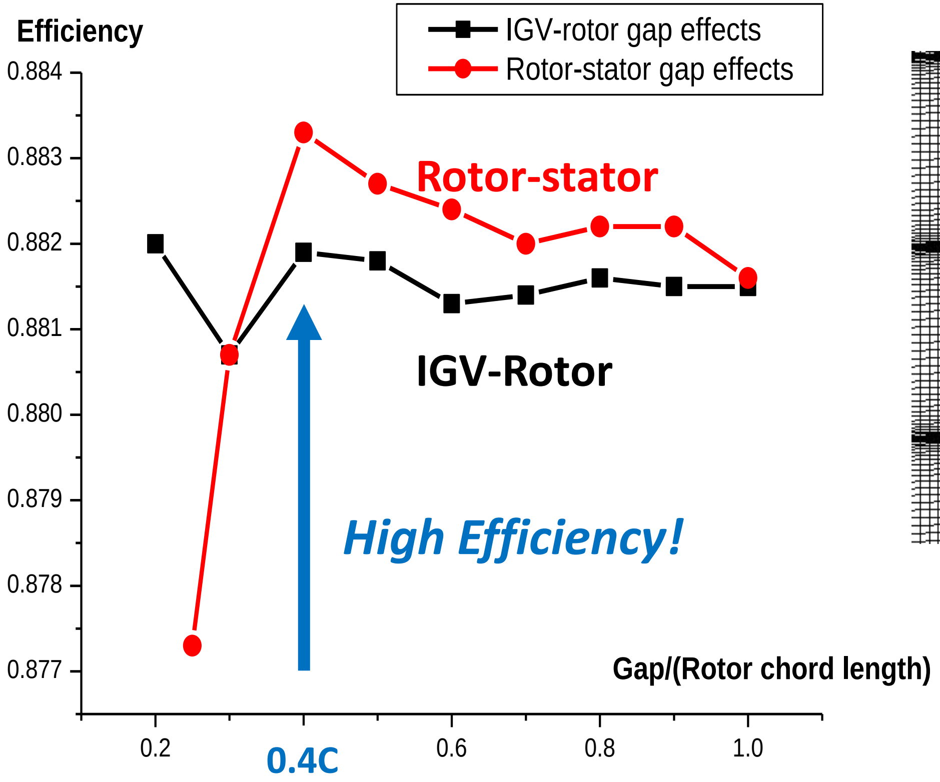


(b) 50% Intra-row Gap

Aeroelastic-Aerodynamic 'Balancing Act': Intra-row Gap Effect (3-row Lyon Compressor)

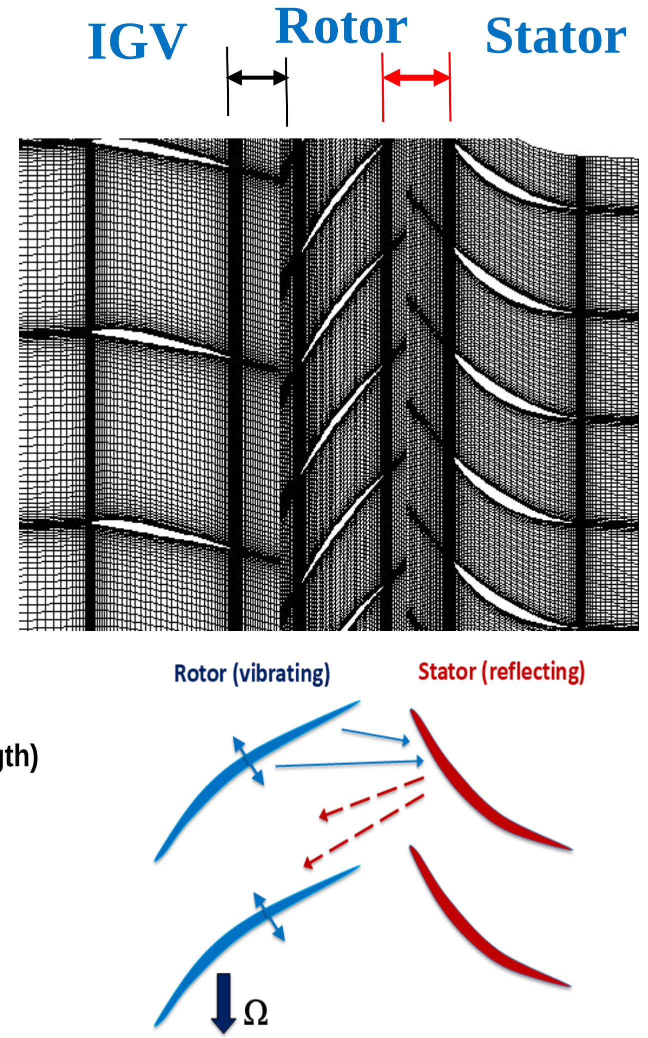
(Single-passage Time-Domain Multi-disturbance Fourier Solutions, Li & He 2005)

Efficiency (η_{is})

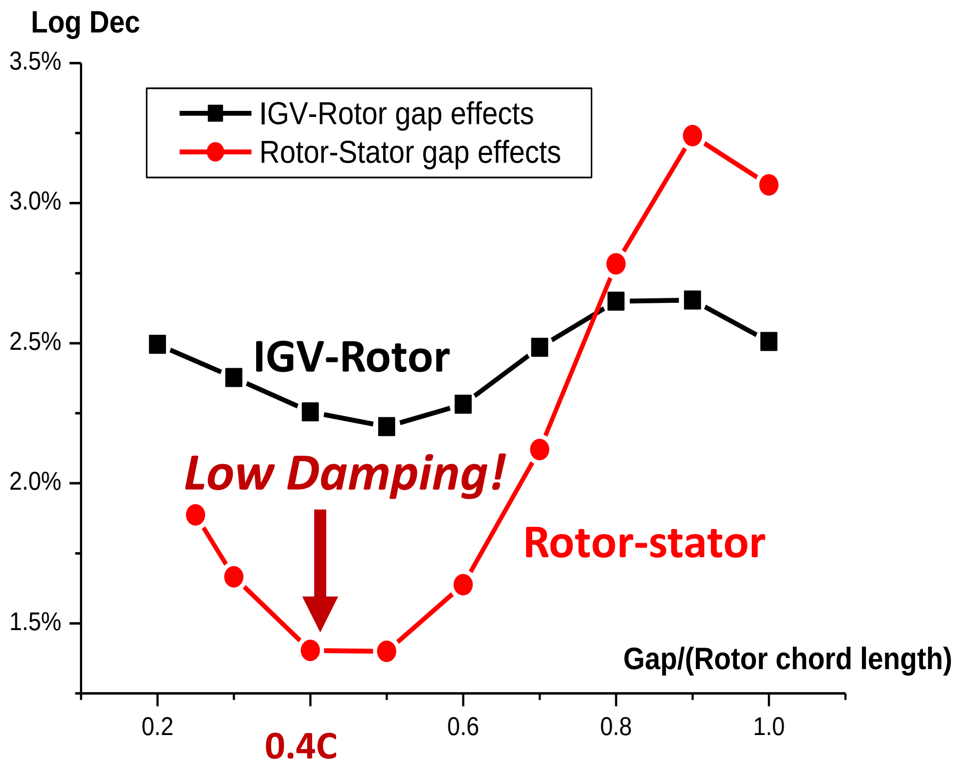


~0.7% η change

(rotor-stator gap: 0.25C ➔ 0.4C)



Rotor Aero-damping

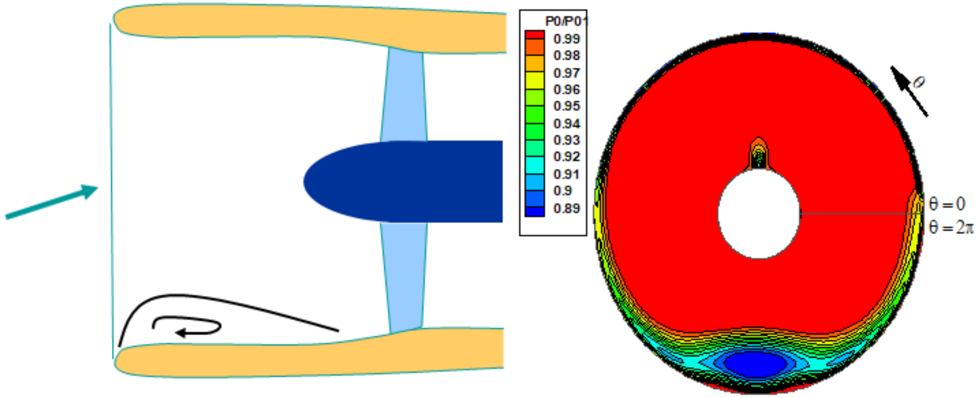


>100% Aero-damping change

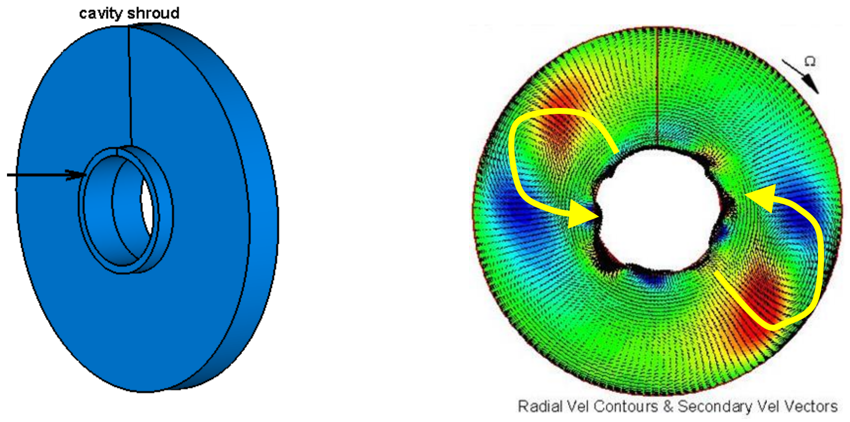
(rotor-stator gap: 0.4C ➔ 0.9C)

Time-domain Spatial Fourier Spectral Methods

- Non-axisymmetric flows: Steady or Unsteady (*Externally-driven or Self-excited*)



Intake Lip Flow Separation at Angle of Attack

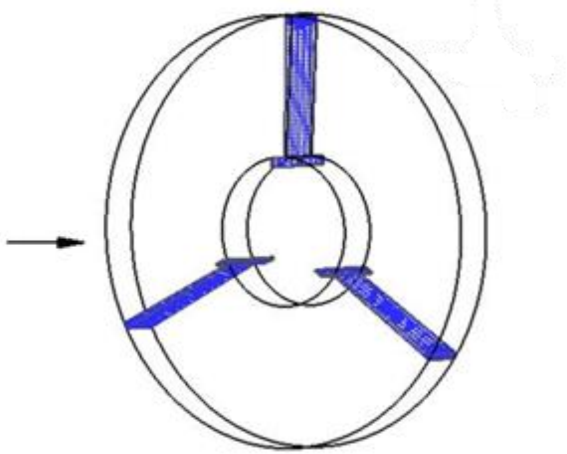


Self-excited Unsteady Cavity Flow

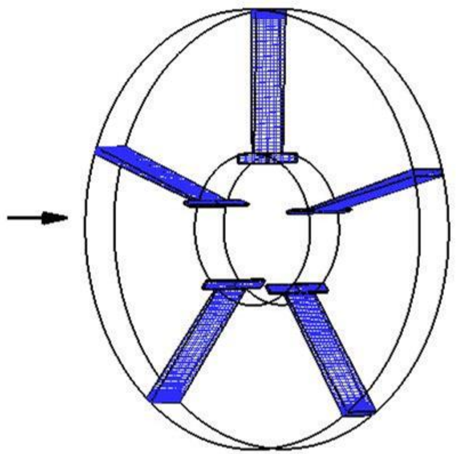
Circumferential (θ) Mesh-Pointwise Fourier Spectrum

$$U(x, r, \theta, t) = \bar{U}(x, r, t) + \sum_{n=1}^{N_f} [A_n(x, r, t)\cos(n\theta) + B_n(x, r, t)\sin(n\theta)]$$

- Fully time–domain (no frequency/periodicity needed)
- Still $2N_f+1$ unknowns for N_f harmonics

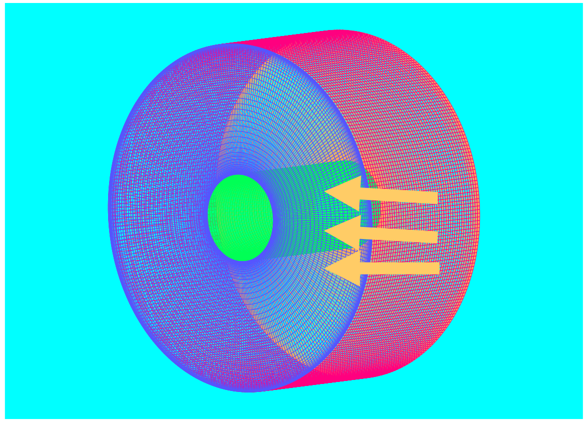


1 harmonic
(3 mesh cells/blocks)

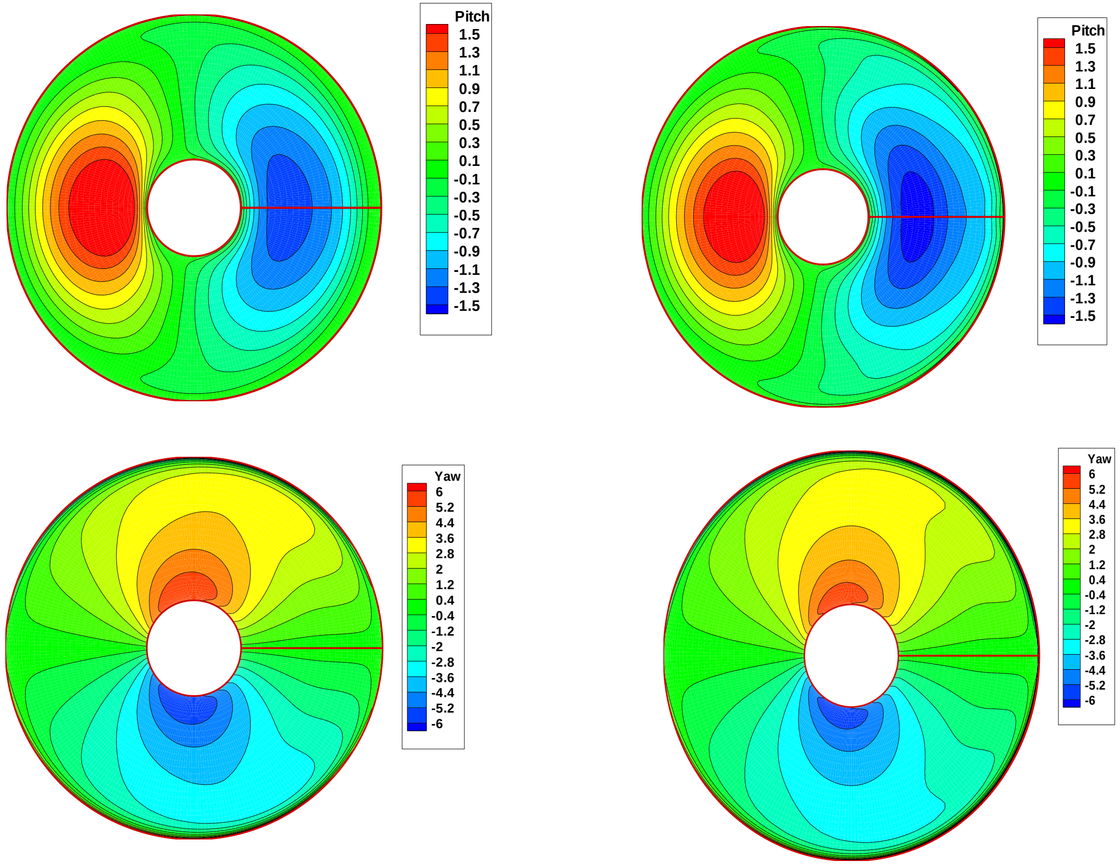


2 harmonics
(5 mesh cells/blocks)

Duct subject to 10° crosswind *(He 2006)*



- **Circumferential Mesh Cells:**
  - ***Direct Solution*** *(360°):* ***300***
  - ***Fourier Spectral*** *(5 harmonics):* ***11***
- **Same Mesh Points in x, r directions**



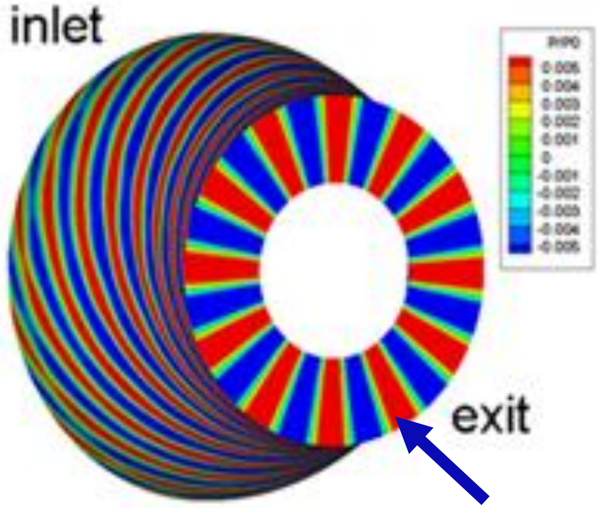
Pitch Angle

Yaw Angle

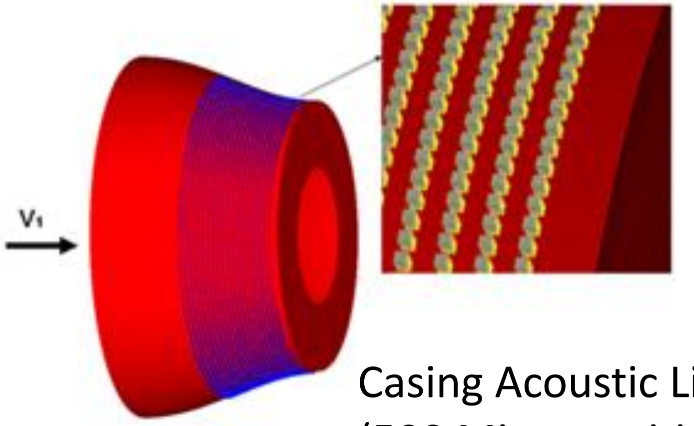
Fourier Solution (11 cells)
(Constructed Full Domain)

Direct Solution (300 cells)

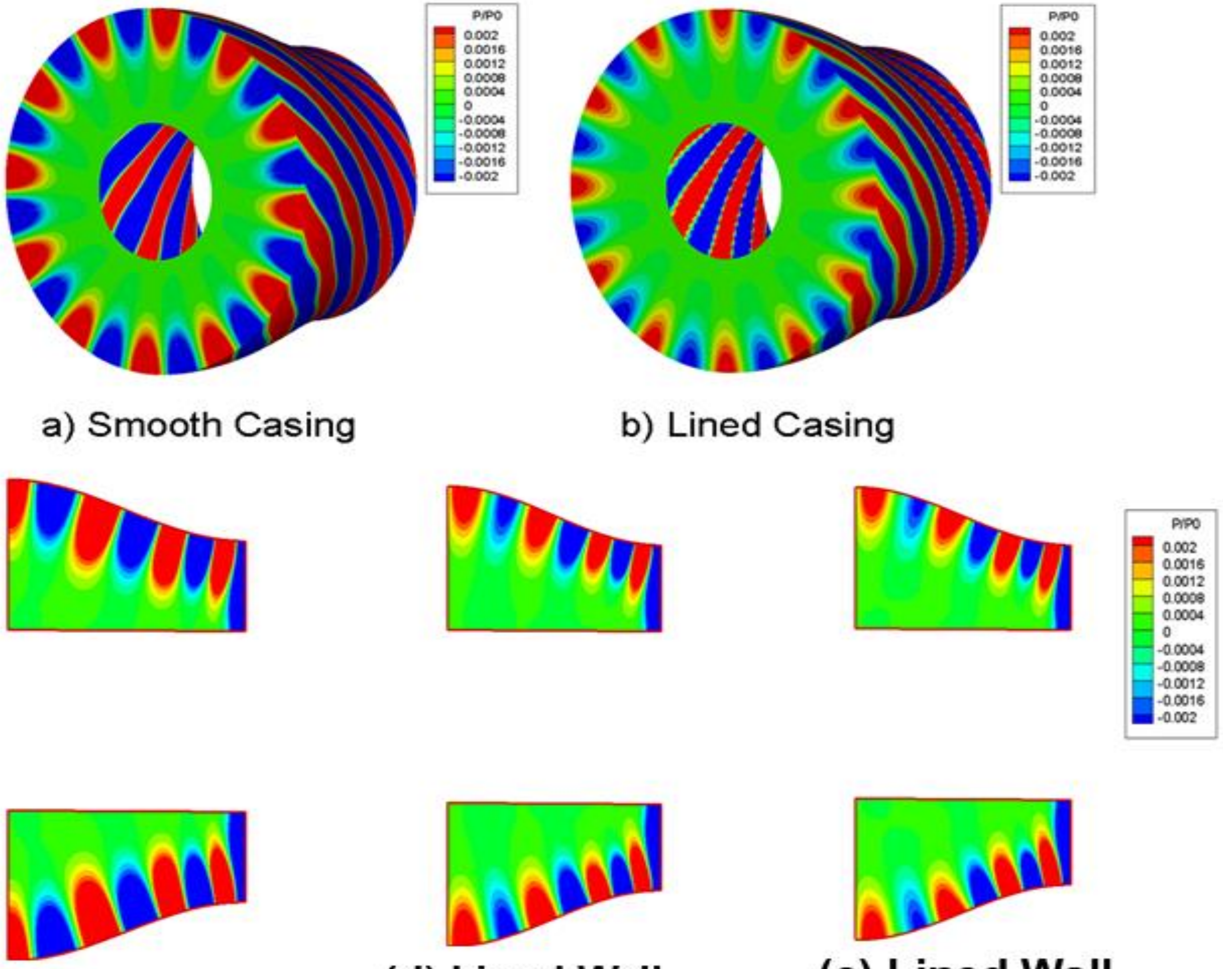
Fan Tone-Noise Propagation in Intake: *Effect of Casing Liner* (He 2013)



Exit Acoustic Disturbances
from 12 Rotating Fan Blades



Casing Acoustic Liner
(500 Micro-cavities/30° Sector)
(fine-mesh blocks)



a) Smooth Casing

b) Lined Casing

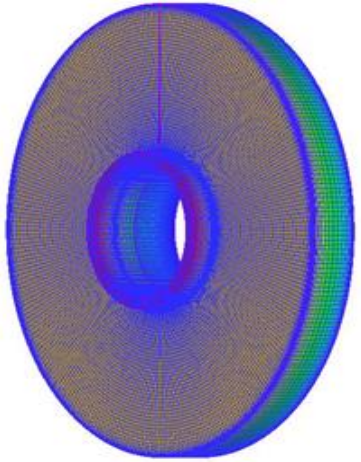
(c) Smooth Wall

(d) Lined Wall
(Direct Solution solving __500 cavities__)

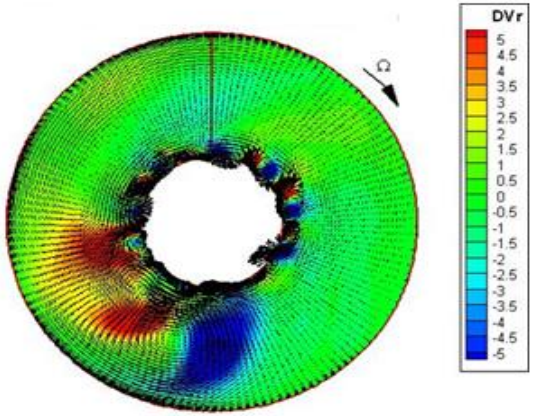
(e) Lined Wall
(Block-Spectral solving __15 cavities__)

Cavity Flow & Heat Transfer (self-sustained: *Coriolis vs. Pressure Forces, He 2011)*

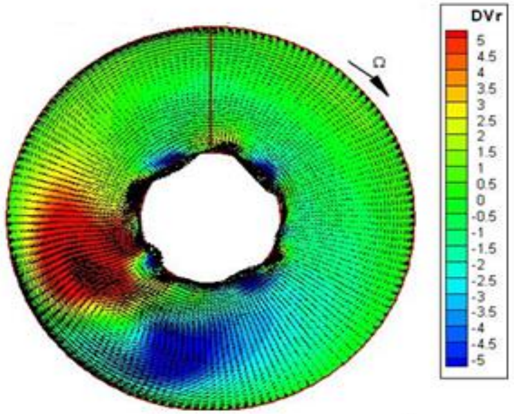
Instantaneous Radial Velocity Contours & Velocity Vectors



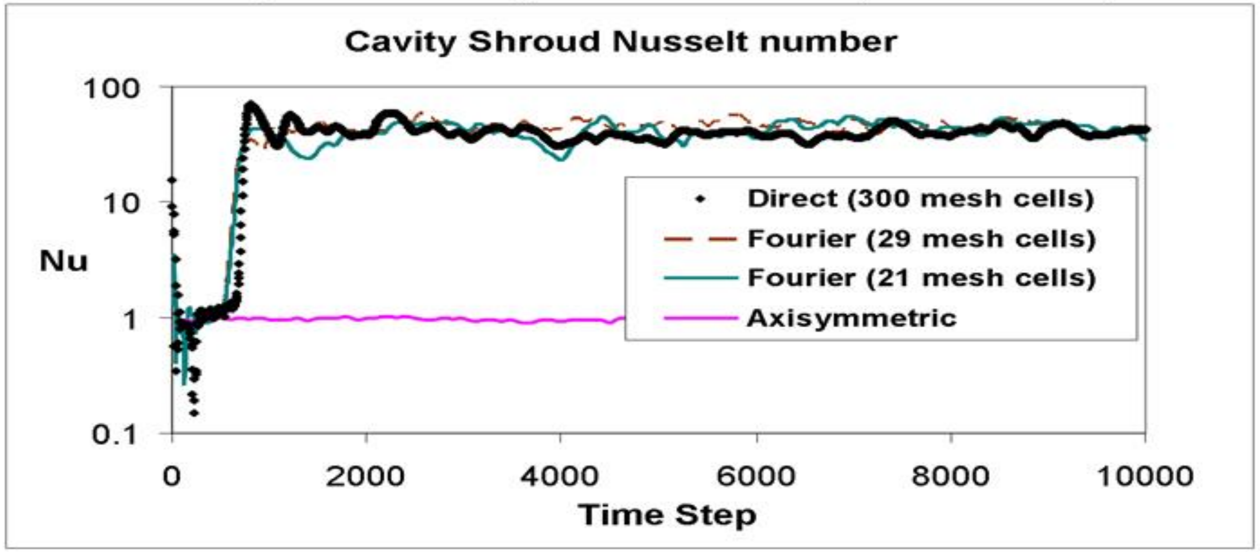
(a) Mesh (Direct Solution)



(b) Direct Solution
(300 mesh cells)



(c) Fourier Solution
(29 mesh cells)



(d) Nusselt Number Time Trace

- Self-excited unstable flow patterns well captured with O(10) less mesh cells
- Statistic-mean changes due to instabilities well captured, far less sensitive than instantaneous flow field

'Hamonic Balance' - *A* Preliminary to Frequency-Domain Methods

- ***The Label Says What It Does:***

1) **Nonlinear Flow Equation Set** (including $\partial U/\partial t$): $\boldsymbol{R(U)=0}$

2) **Fourier Spectrum of N_f harmonics:** $\boldsymbol{U = \overline{U} + \sum_{n=1}^{N_f}[A_n\cos(n\omega t) + B_n\sin(n\omega t)]}$, **($2N_f$+1 unknowns)**

3) ***Substitute into Flow Equations and Expand:*** $\boldsymbol{R(\overline{U} + \sum_{n=1}^{N_f}[A_n\cos(n\omega t) + B_n\sin(n\omega t)]) = 0}$

4) **Group** **coefficients for each** **Harmonic** **respectively for** $\boldsymbol{\overline{U}}$, $\boldsymbol{\cos(n\omega t)}$ **and** $\boldsymbol{\sin(n\omega t)}$ ➔ $\boldsymbol{2N_f}$ **+1 groups**

5) **Balance** **each** **Harmonic** **group respectively** ➔ $\boldsymbol{2N_f}$ **+1 equations for** $\boldsymbol{2N_f}$ **+1 unknowns**

- **Frequency-Domain Method:** ***An Unsteady Problem*** ➔ ***A Set of Steady Problems***

Closing 'Deterministic Stresses' (Adamczyk, 1985) by Computing Them
- *A* Preliminary to Nonlinear Harmonic Method

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- **'Deterministic' – sum of periodic disturbances (primary and higher harmonics)**

  -blade row interactions/distortion (frequencies linked to shaft speed)

  -blade aeromechanics (frequencies of structural modes)

- **Cast Unsteady Disturbances equations in frequency domain with known primary frequency ω:**

$$\boldsymbol{U}' = \sum_{\boldsymbol{n=1}}^{\boldsymbol{N_f}} [\boldsymbol{A_n}\cos(\boldsymbol{n\omega t}) + \boldsymbol{B_n}\sin(\boldsymbol{n\omega t})]$$

  - One unsteady problem ➔ $2N_f$ "steady" problems (for a given time-average/steady base)

  - Cost benefit if N_f is small (e.g. N_f=1 for standard blade flutter analysis)

- **Solve Harmonics Eq. (thus 'Deterministic Stresses') while coupling with the Base (Time-averaged Eq.)**

  - More accurate than Empirical models

  - More cost-efficient than Multi-passage URANS

Time-averaged Base & Unsteady Disturbances: Balancing Act

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Consider: *1-D Momentum for Compressible Inviscid Flow)*

$$\frac{\partial \rho u}{\partial t} + \frac{\partial \rho u u}{\partial x} = -\frac{\partial P}{\partial x}$$

i) **Variable Decomposition** (based on ***Time-averaging***):

Primary Variables: $\rho = \overline{\rho} + \rho'$ **Secondary Variables:** $P = \overline{P} + P'$

$\rho u = \overline{\rho u} + (\rho u)'$ $u = \overline{u} + u'$ $(\overline{u'} = 0\ !)$

ii) **Equation Decomposition** (no assumption invoked):

$$\left\{ \frac{\partial}{\partial x}\left(\overline{\rho u}.\overline{u} + (\rho u)'u'\right) + \frac{\partial \overline{P}}{\partial x} \right\} + \left\{ \frac{\partial (u)'}{\partial t} + \frac{\partial}{\partial x}\left(\overline{\rho u}\, u' + \overline{u}\,(\rho u)'\right) + \frac{\partial P'}{\partial x} \right\} = 0$$

Base State (Nonlinear) ***Unsteady Disturbances ('quasi-linear')***

iii) **Time-averaging for the Base** (still no assumption invoked):

$$\frac{\partial}{\partial x}\left(\overline{\rho u}.\overline{u} + \overline{(\rho u)'u'}\right) + \frac{\partial \overline{P}}{\partial x} = 0$$

iv) **Balancing Unsteady Disturbances** *(quasi-linear on top of Base State)*:

$$\frac{\partial (\rho u)'}{\partial t} + \frac{\partial}{\partial x}\left(\overline{\rho u}\, u' + \overline{u}\,(\rho u)'\right) + \frac{\partial P'}{\partial x} = 0$$

Modelling Consistence for Time-Averaged Equation

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Original Eq. $$\frac{\partial \rho u}{\partial t} + \frac{\partial \rho u u}{\partial x} = -\frac{\partial P}{\partial x}$$

$\overline{u'} = 0$

$$\Rightarrow \underbrace{\left\{ \frac{\partial}{\partial x}\left(\overline{\rho u}.\overline{u} + (\rho u)'u'\right) + \frac{\partial \bar{P}}{\partial x} \right\}}_{\textit{Base State (Nonlinear)}} + \underbrace{\left\{ \frac{\partial (\rho u)'}{\partial t} + \frac{\partial}{\partial x}\left(\overline{\rho u}\, u' + \overline{u}\,(\rho u)'\right) + \frac{\partial P'}{\partial x} \right\}}_{\textit{Unsteady Disturbance ('quasi-linear')}} = 0$$

$$\Rightarrow \boxed{\frac{\partial}{\partial x}\left(\overline{\rho u}.\overline{u} + \overline{(\rho u)'u'}\right) + \frac{\partial \bar{P}}{\partial x} = 0}$$

- **Requirement for Time-Averaged Eq: unsteady disturbances terms ➔ 0 when time-averaged**
  (warranted as all disturbances are quasi-linear in time)

- **Other averaging options (other than Time-averaging): Time-averaged Eq. may be less consistent**
  (e.g. Favre-averaging: $u = \tilde{u} + u''$, $\tilde{u} = \overline{\rho u}/\overline{\rho}$ ➔ $\overline{u''} \neq 0$)

Nonlinear Harmonic Method *(He 1996, Ning & He 1998)*

1D Momentum Eq.:

$$\frac{\partial \rho u}{\partial t} + \frac{\partial \rho u u}{\partial x} = -\frac{\partial P}{\partial x}$$

Fourier Spectrum of N_f harmonics:

$$\rho u = \overline{\rho u} + \sum_{n=1}^{N_f} [\,(A_{\rho u})_n \cos(n\omega t) + (B_{\rho u})_n \sin(n\omega t)]$$

(2N_f +1 unknowns)

Hamonic Balance →
$2N_f$ +1 'Steady' Eqs:

$$\frac{\partial}{\partial x}\left(\overline{\rho u}.\overline{u} + \overline{(\rho u)' u'}\right) + \frac{\partial \overline{P}}{\partial x} = 0 \qquad (n=0\,!)$$

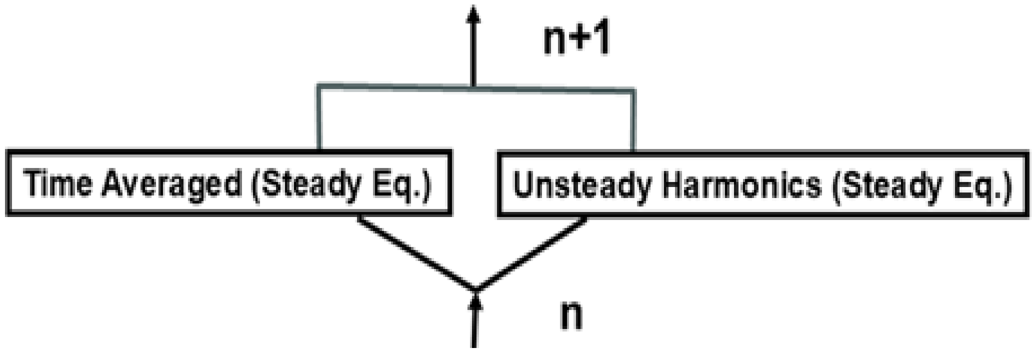
$$-n\omega\,(A_{\rho u})_n + \frac{\partial}{\partial x}\left[\,\overline{\rho u}(B_u)_n + \overline{u}\,(B_{\rho u})_n + (B_p)_n\right] = 0, \qquad (n = 1, 2, .., N_f)$$

$$n\omega\,(B_{\rho u})_n + \frac{\partial}{\partial x}\left[\,\overline{\rho u}\,(A_u)_n + \overline{u}\,(A_{\rho u})_n + (A_p)_n\,\right] = 0, \qquad (n = 1, 2, .., N_f)$$

Closure of 'Deterministic Stress':

$$\overline{(\rho u)' u'} = \frac{1}{2}\sum_{n=1}^{N_f}[(A_{\rho u})_n (A_u)_n + (B_{\rho u})_n (B_u)_n\,]$$

Strongly Coupled 'Steady' Solution:



Time spectral ('Harmonic Balance') Method *(Hall et al, 2002)*

- ***Extra 'cross-coupling' terms may be included in $2N_f$+1 Harmonic Balance Eq. (at extra cost!)***

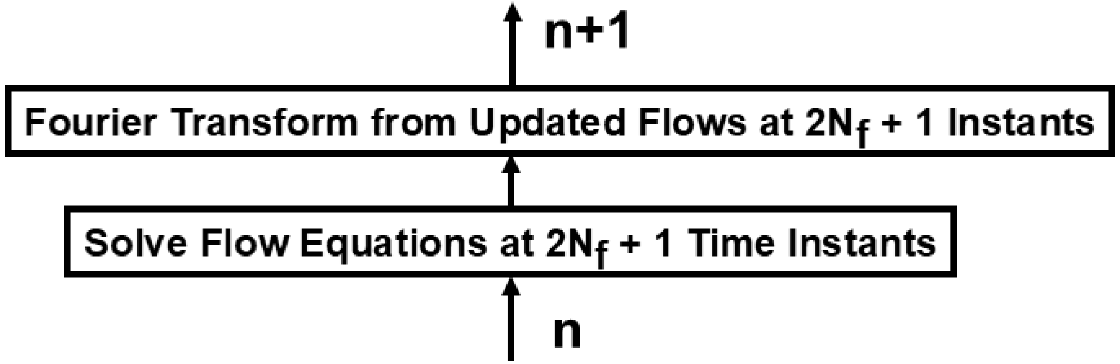
- ***A different solution ('collocation time-spectral') method is chosen instead.***

-Starting point: $\frac{\partial U}{\partial t} = R(U)$ and $U = \overline{U} + \sum_{n=1}^{N_f}[\, A_n \cos(n\omega t) + B_n \sin(n\omega t)]$ **($2N_f$ +1 Unknowns)**

- Equations hold at $2N_f + 1$ time instants: $(\frac{\partial U}{\partial t})_i = R(U_i)$ (i =1, 2, …., $2N_f$+1)

i.e. $\sum_{n=1}^{Nf}[n\omega(-A_n\, sin(n\omega t_i) + B_n\, cos(n\omega t_i)] = R(U_i)$, (i =1, 2, …., $2N_f$+1)

-Solve $2N_f + 1$ coupled eqs, & Update $2N_f + 1$ knowns by Fourier-transform at each iteration



- ***Fully nonlinear including cross-coupling implicitly.***
- ***Easy to implement including turbulence model eq.***
- ***'Harmonic Balance'? - neither used, nor needed.***

Time spectral Method for Concurrent Aerodynamic-Aeroelastic Optimization
(Wang & He, 2009, He & Wang 2012)

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- Take Time-domain Flow Equations at ***3 phase angles*** for single harmonic *(He 2008):*

$$\omega t_1 = 0°, \quad solution\ for\ U_1 = \overline{U} + A,$$
$$\omega t_2 = 90° \quad solution\ for\ U_2 = \overline{U} + B,$$
$$\omega t_3 = -90° \quad solution\ for\ U_3 = \overline{U} - B,$$

→ $\overline{U}$, A, B directly without FT

- Similarly take Adjoint Equations (variable λ) at ***3 phases*** for single harmonic:

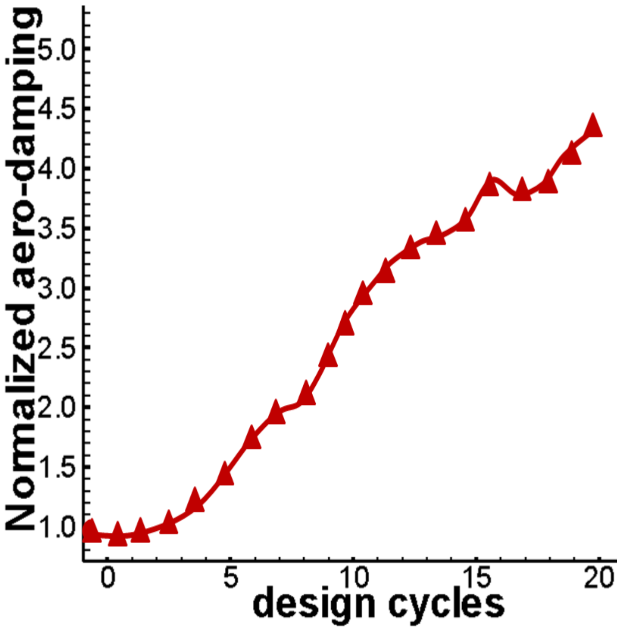
$$\omega t_1 = 0°, \quad solution\ for\ \lambda_1,$$
$$\omega t_2 = 90° \quad solution\ for\ \lambda_2,$$
$$\omega t_3 = -90° \quad solution\ for\ \lambda_3,$$

→ Sensitivities of base flow $\overline{U}$ and unsteady harmonic (A, B) to blade geometry perturbations.

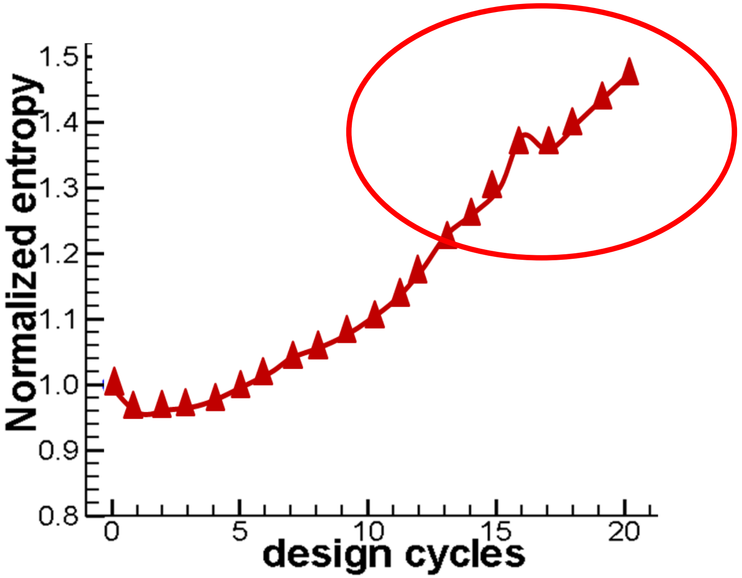
→ **Concurrent Optimization to increase Aeroelastic Stability (Aero-damping↑) without a compromise in Aerodynamic Performance (Aero-loss↓).**

Why Concurrent D/O? - Limitation of Single-discipline D/D

Task: shaping blade to increase stability/damping
(for a given high η aero-design)



Aero-damping

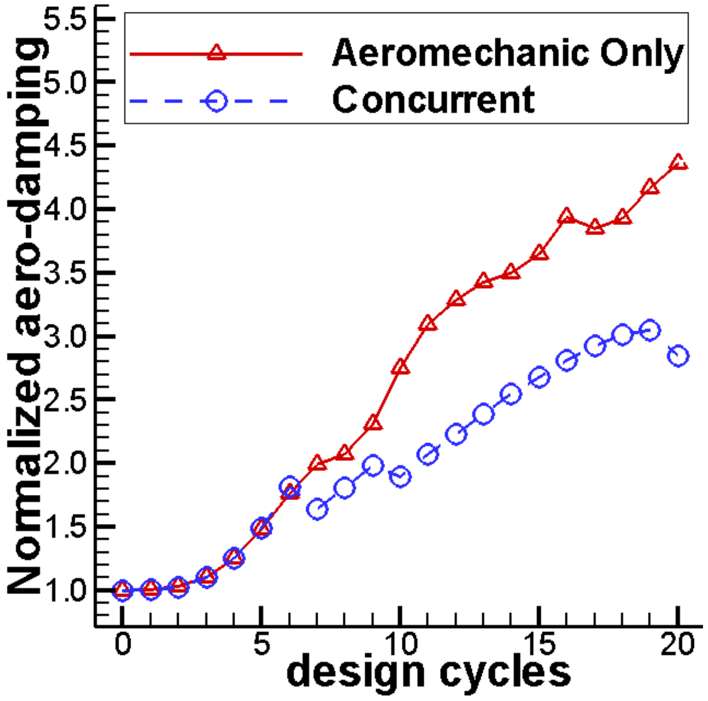


Aero-loss

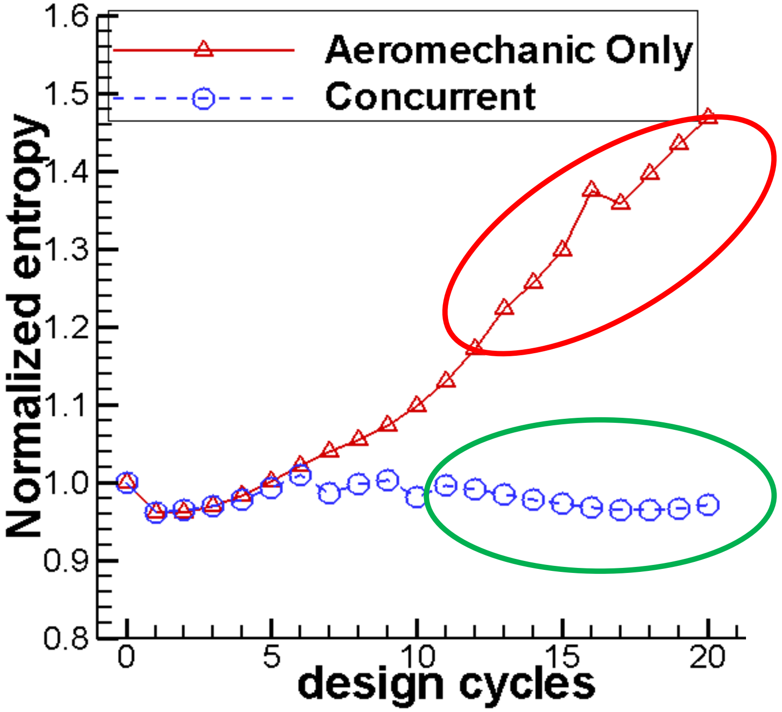
- ***Aeroelastic-only design compromises aero-performance !***

Concurrent D/O:

To ask for both Aerodynamic and Aeroelastic gains at the same time



Aero-damping



Aero-loss

Multi-point Adjoint Aerodynamic-Aeroelastic D/O (DLR Transonic Rotor)

(Wang & He 2009, He & Wang 2011)

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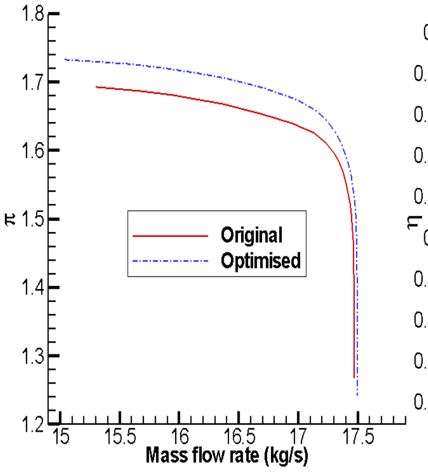
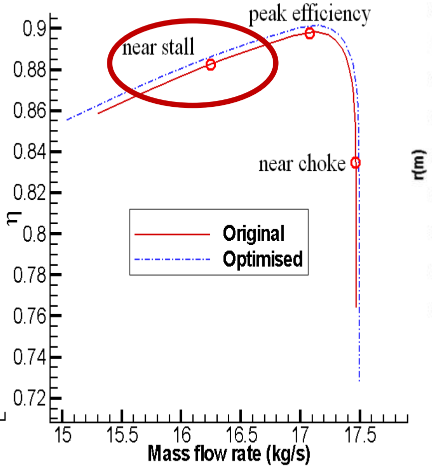
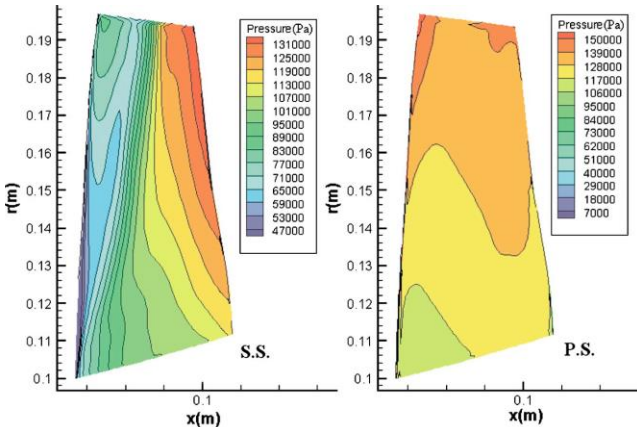
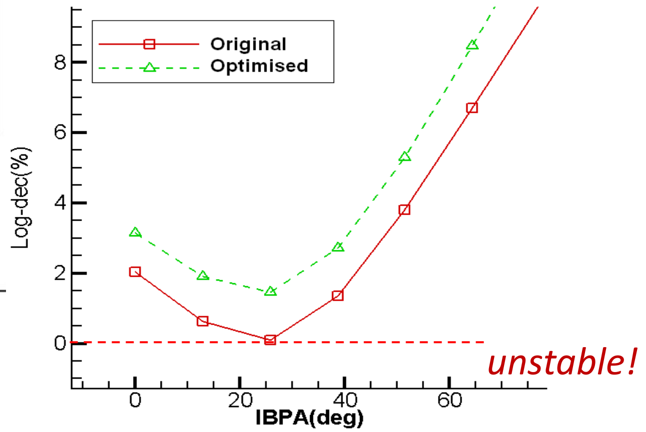
Aero-performance







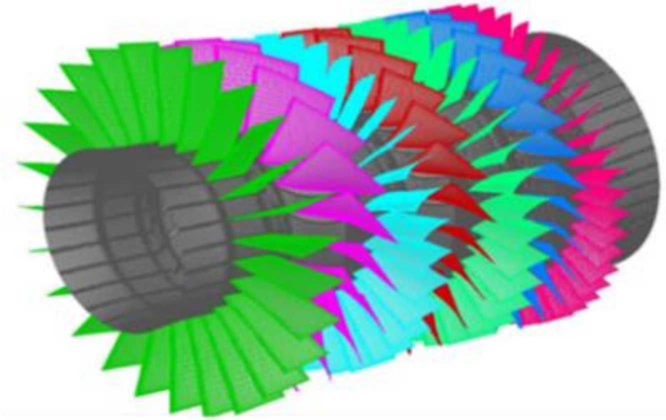
Aero-damping (near-stall)



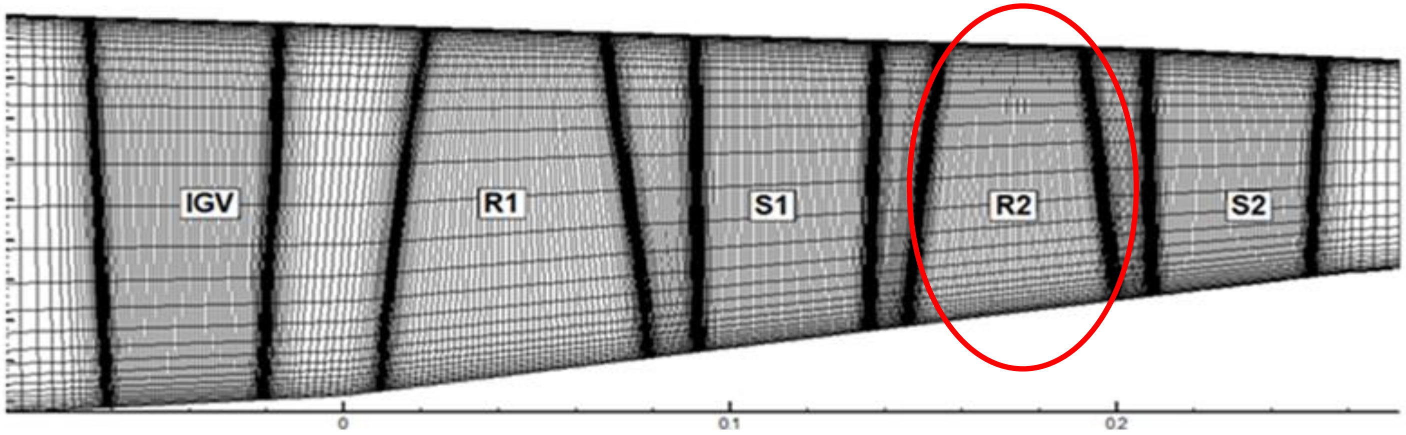
Optimized vs *Original*

Operating point	Pressure ratio	Efficiency	Damping (Log-dec %)
Near stall	1.716 *(1.667)*	**89.57** ***(88.29)***	**1.6** ***(0.1)***
Peak efficiency	1.661 *(1.626)*	**89.76** ***(89.70)***	**3.2** ***(2.7)***
Near choke	1.449 *(1.421)*	**83.60** ***(83.47)***	**3.9** ***(3.4)***

Nonlinear Harmonic Multi-stage Solution *(Rotor-Rotor/Sator-Stator Interactions)*
(Closing Adamczyk "Deterministic Stresses" by computing them, efficiently)



Multistage Compressors



- **General Multi-disturbance Fourier Model** (He 1992):

$$U(x,t)_{R2} = \overline{U}(x)_{R2} + U_{S1\text{-}R2}(x,t) + U_{R1\text{-}R2}(x,t)$$

- **S1-R2 Interface**: *Rotating Harmonics from R1 in Stator (S1)* ➔ *Stationary Harmonics from R1 'seen' by R2*

- **R-R/S-S Interaction Effects** ('Clocking' /'Aperiodic Variation'): *Efficiently Reconstructed with Stationary Harmonics*

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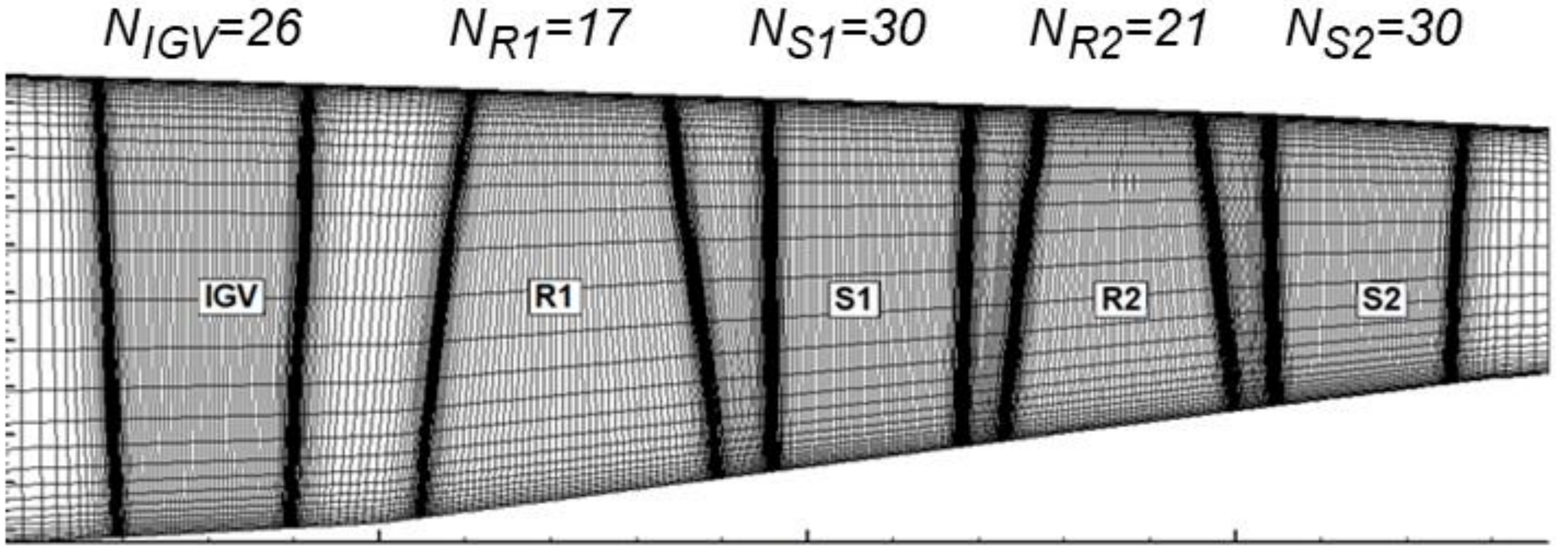
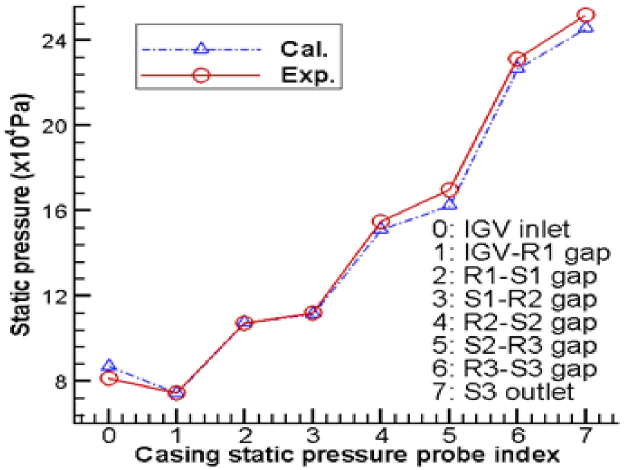
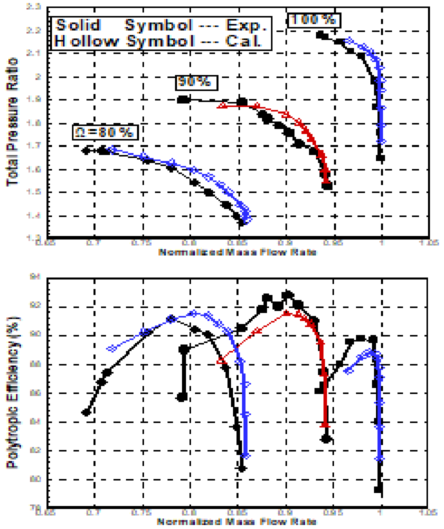
Coupled Unsteady Multi-stage Solution (Nonlinear Harmonic Method)

(He et al 2002)

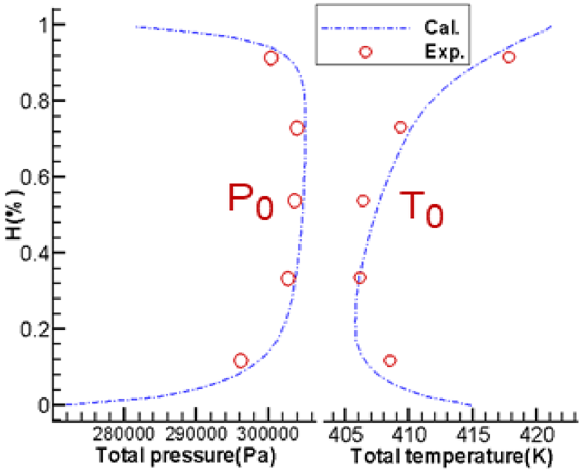




(a) Casing Pressure Probe



(b) 2-stage Performance



(c) Exit Spanwise Traverses

Rotor-Rotor/Stator-Stator Interferences *(Nonlinear Harmonic Method)*
Stator-Stator ‘Clocking’ and Rotor-Rotor ‘Aperiodicity’ *(He et al 2002)*

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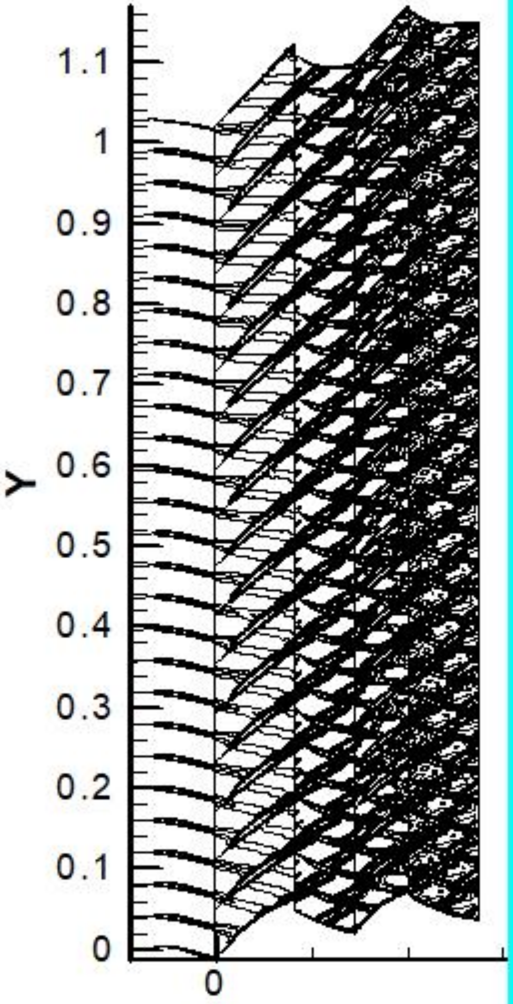
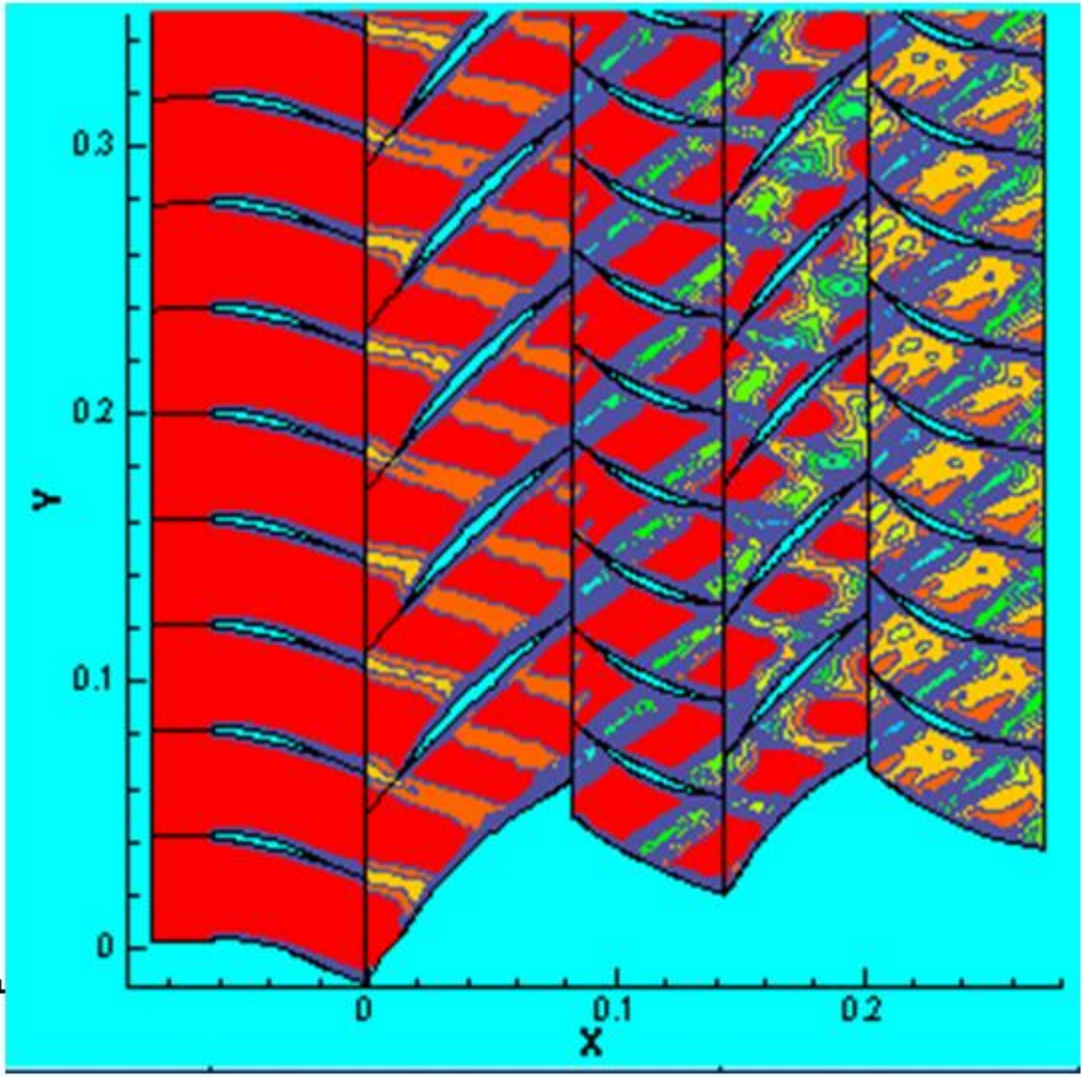
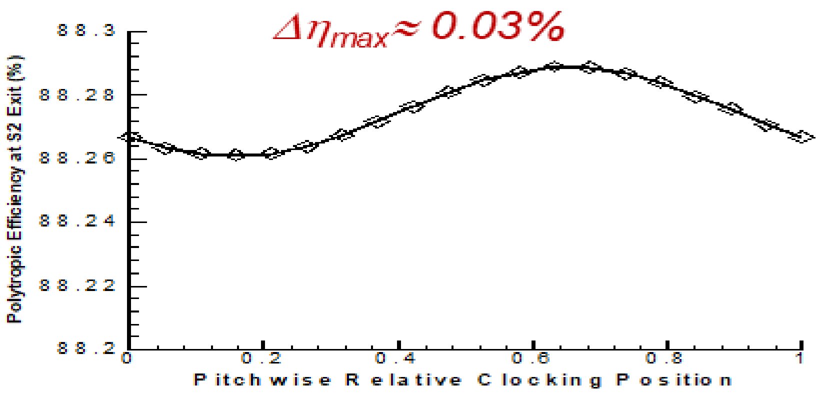


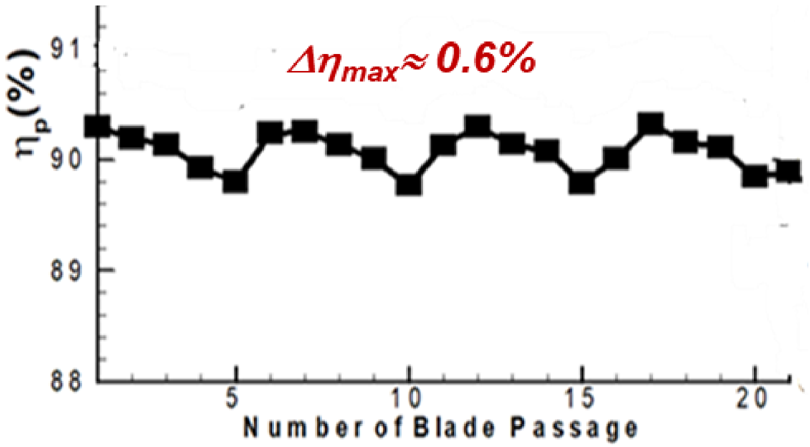
(a) Overall Domain



(b) Close-up



(a) Stator1 - Stator2 Clocking
(N_{S1} =N_{S2}=30)



(b) Rotor2 Passage Aperiodicity
(N_{R1}=17, N_{R2}=21)

Closing Remarks

- **Multi-fidelity models are needed for Designs & Analyses, particularly in Multi-disciplinary Multi-component Interactive Settings (*Aerodynamics is Only Part of the Problem!*)**

- **The filtering (truncating) ability of a Fourier model ➔ More efficient prediction & clearer understanding of what the related methods can (& cannot) do.**

- **Progress in past 30 years in the development of Fourier methods for turbomachinery ➔ Part of Turbomachinery CFD Ecosystem.**

- **Continued development and applications of truncated/reduced methods aided by physical insight and computational modelling/method understanding are expected.**