Surface patterning and the effects on dynamic characteristics of annular hole-pattern seals

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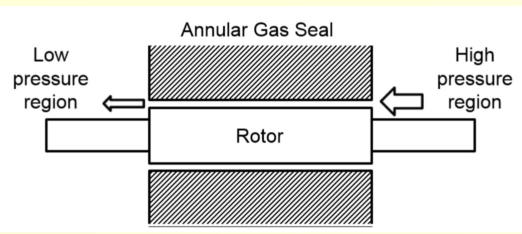
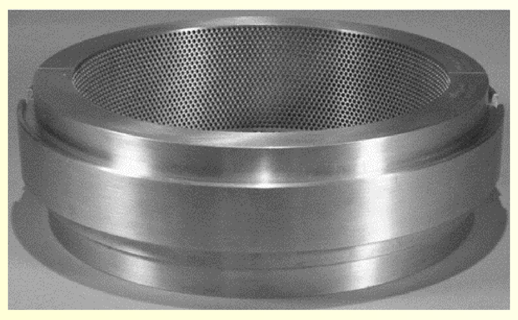
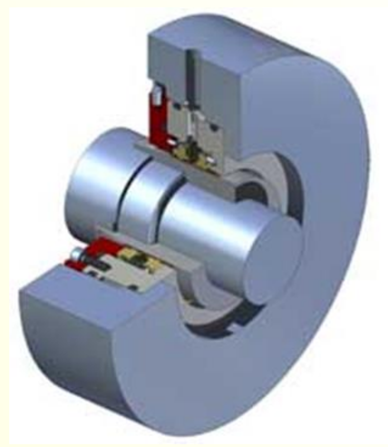
Introduction

Non-Contacting Annular Gas Seals

- reduce leakage rate between different pressure regions
  - acceleration and deceleration of the process fluid as it passes through a small restriction area followed by a subsequent expansion region arranged in an surface pattern
  - convoluted flow path is therefore very important to the performance of the annular gas seal
- strong influence on the dynamic characteristics of the entire machine







Goals

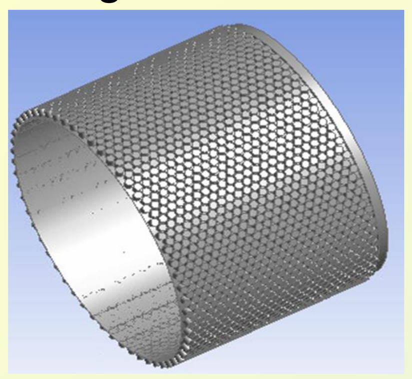
- To Investigate the effect of surface patterning
  - on leakage rate in hole-pattern seals
  - on rotor dynamic properties

alternately arranged surface pattern

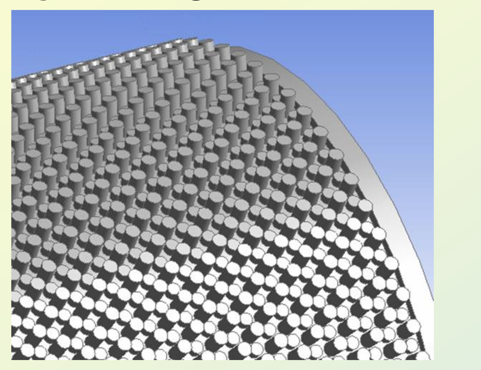
Methodology

Computational Model

Regular vs Alternately Arranged Pattern



Baseline Model



Alternately arranged surface patterning obtained through parameterization

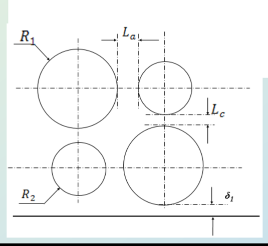
Parameterization

Constant Parameters

Parameter	Description	Base Value
Dr	Rotor Diameter	114.34 [mm]
Cr	Radial Clearance of Seal	0.204 [mm]
Ls	Seal Length	86 [mm]
Ds	Seal Diameter	114.74 [mm]
δ_1	Space between Outlet and Holes	0.8 [mm]
δ_2	Space between Outlet and Holes	0.45 [mm]

Design Variables

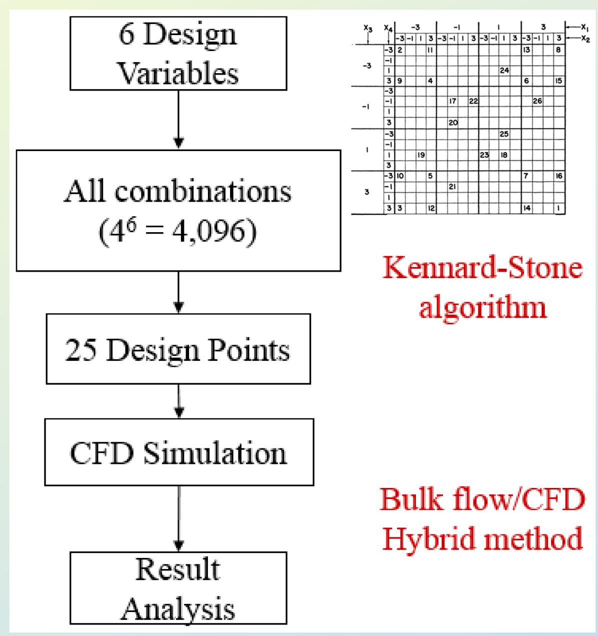
Parameter	Description	Base Value	List of Feasible Values in the Design Space
R_1	Radius of Larger Holes	1.5875 [mm]	1.1906, 1.5875, 1.9844, 2.3812 [mm]
c	Ratio of Smaller Hole Radius to Larger Hole Radius	1	0.9,0.75, 0.6,0.45
H_1	Larger Hole Depth	3.3020 [mm]	1.6510, 2.4765, 3.3020, 4.1275 [mm]
H_2	Smaller Hole Depth	3.3020 [mm]	1.6510, 2.4765, 3.3020, 4.1275 [mm]
R_a, , Determines N_1	Ratio of Space to Radius in Axial Direction	0.277	0.1, 0.2, 0.3, 0.4
R_c, , Determines N_2	Ratio of Space to Radius in Circumferential Direction	0.277	0.1, 0.2, 0.3, 0.4



$$L_a = (R_1 + R_2)\cdot r_a$$
$$L_c = (R_1 + R_2)\cdot r_c$$
$$N_1 = (L_s - R_1 - R_2)/(R_1 + R_2 + L_a)$$
$$N_2 = (\pi D - R_1 - R_2)/(R_1 + R_2 + L_c)$$

Geometry Variables

Design of Experiments

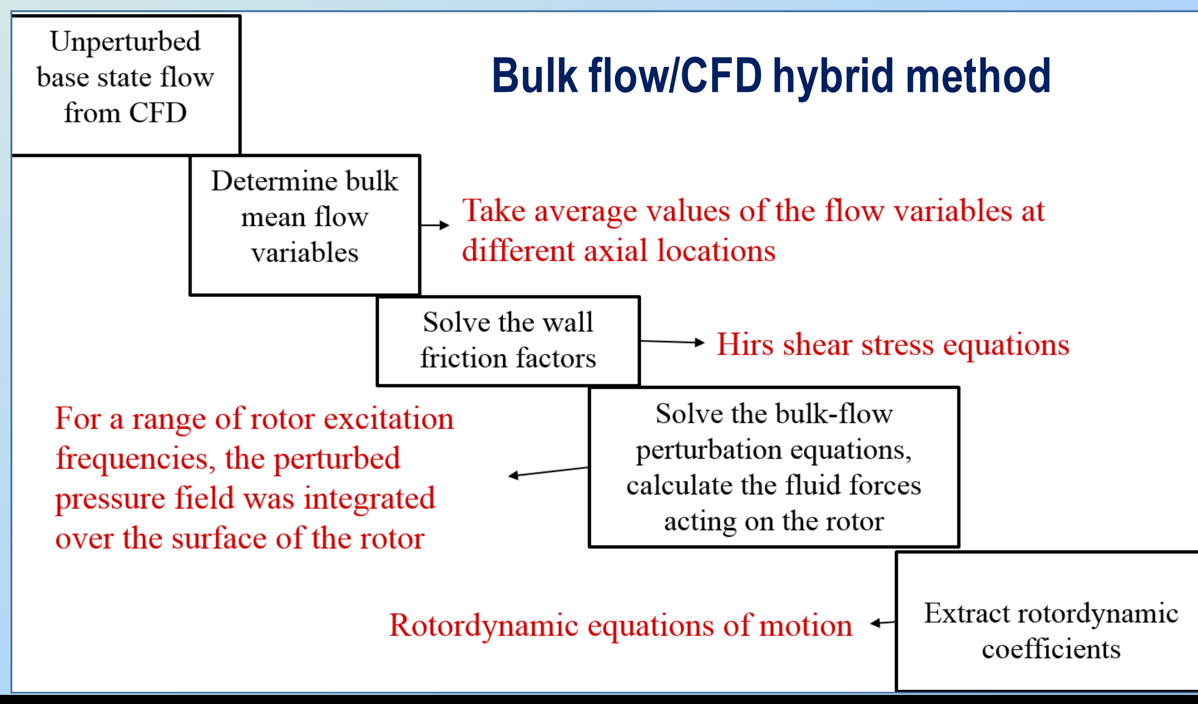


$$-\begin{bmatrix}F_X\\F_Y\end{bmatrix} = \begin{bmatrix}K_{XX} & K_{XY}\\K_{YX} & K_{YY}\end{bmatrix}\begin{bmatrix}X\\Y\end{bmatrix} + \begin{bmatrix}C_{XX} & C_{XY}\\C_{YX} & C_{YY}\end{bmatrix}\begin{bmatrix}\dot{X}\\\dot{Y}\end{bmatrix}$$

The rotor dynamic coefficients

- **Effective Damping**: a widely used single number measure of a rotor dynamic component's stability. Higher effective damping means higher stability of the system

$$C_{eff} = C_{XX}\left(1 - \frac{K_{XY}}{\omega C_{XX}}\right)$$



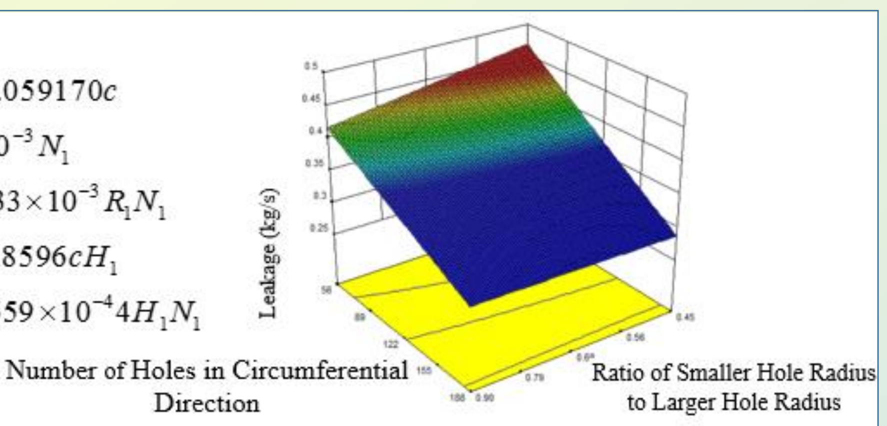
Results

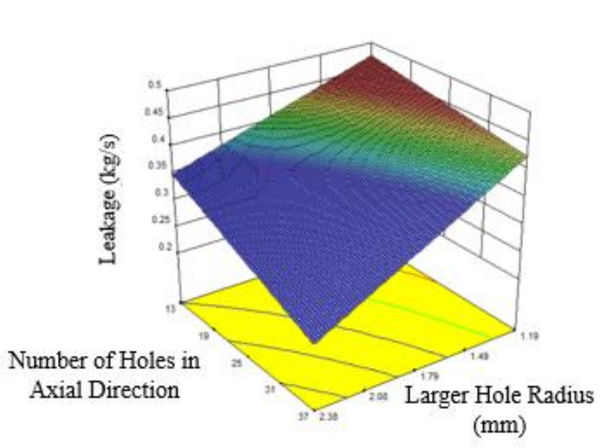
Regression Model and Response Surface

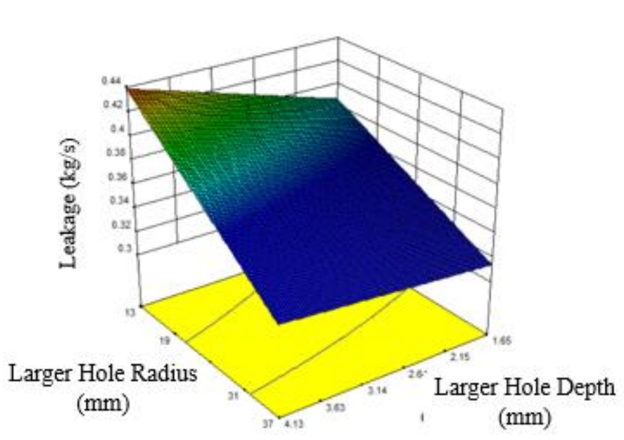
- Regression analysis is a statistical process for estimating the relationships among variables.
- Response surface methodology explores the relationships between several explanatory variables and one or more response variables.
- Regression models are obtained by performing backwards elimination on full quadratic least squares regression models.

Leakage Rate

$$\begin{aligned} Leakage = {} & 0.48045 + 0.044484R_1 - 0.059170c \\ & + 0.054731H_1 + 2.79316\times10^{-3}N_1 \\ & - 1.22638\times10^{-4}N_2 - 2.69333\times10^{-3}R_1N_1 \\ & - 9.47710\times10^{-4}R_1N_2 - 0.038596cH_1 \\ & + 9.83065\times10^{-4}cN_2 - 6.16659\times10^{-4}4H_1N_1 \end{aligned}$$

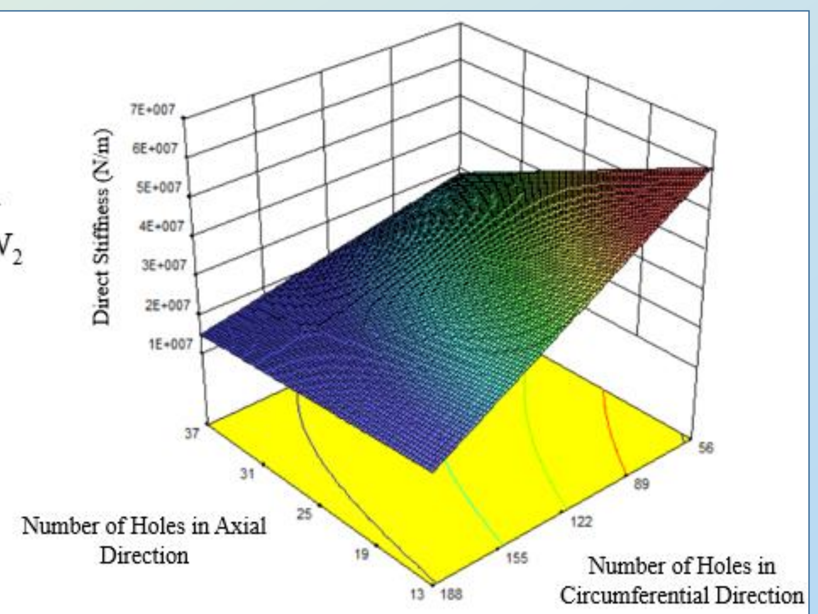






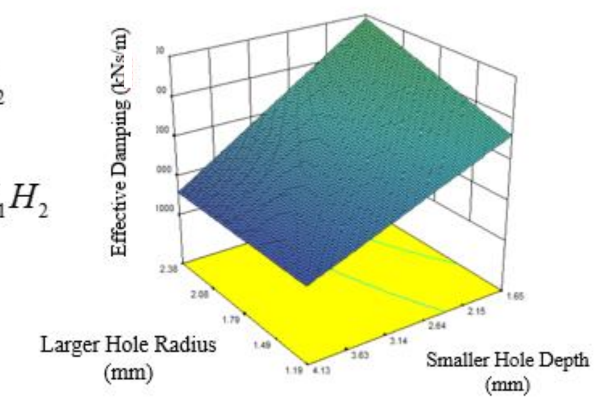
Direct Stiffness

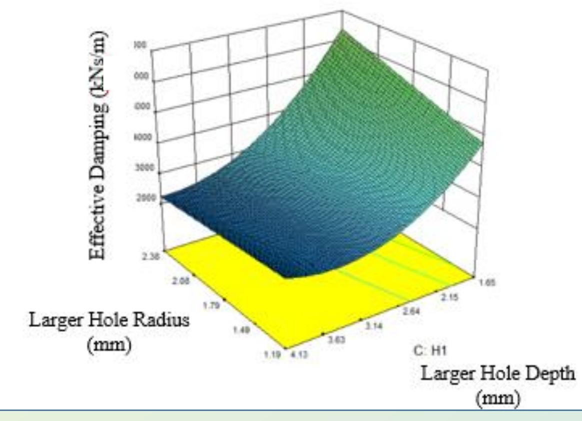
$$\begin{aligned} K_{XX} = {} & 2.00995\times10^{8} - 8.99490\times10^{7}R_1 \\ & + 8.93391\times10^{7}c - 3.54359\times10^{6}H_1 \\ & - 3.58571\times10^{6}H_2 - 1.80243\times10^{6}N_1 \\ & - 4.28962\times10^{5}N_2 + 8643.64890N_1N_2 \\ & + 1.83410\times10^{7}R_1^2 - 7.95180\times10^{7}c^2 \end{aligned}$$

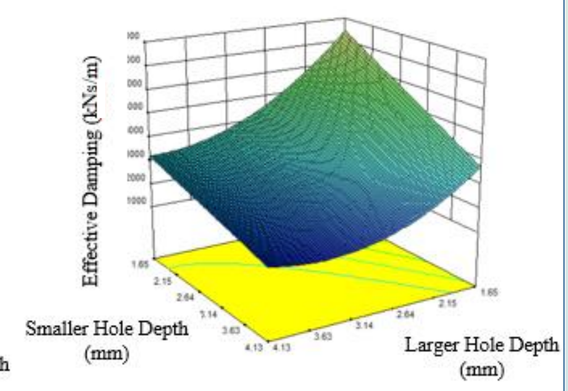


Effective Damping

$$\begin{aligned} C_{eff} = {} & 13635.43929 + 3647.33224R_1 \\ & - 5147.95466H_1 - 1316.05992H_2 \\ & - 68.05623N_1 - 648.90862R_1H_1 \\ & - 426.45157R_1H_2 + 344.66427H_1H_2 \\ & + 697.88314H_1^2 \end{aligned}$$

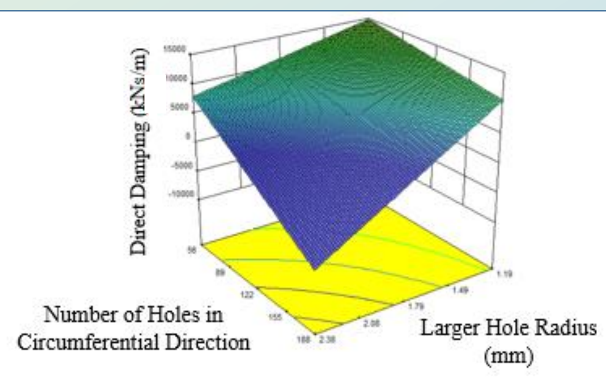


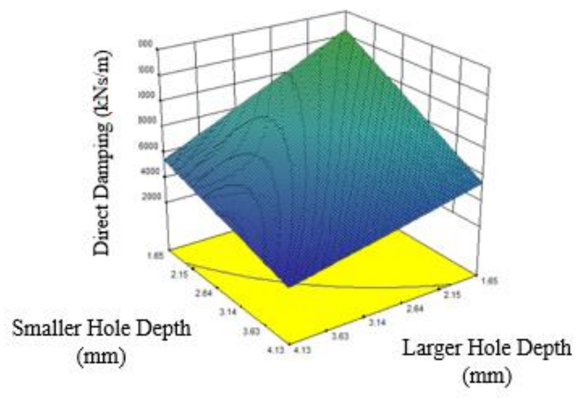




Direct Damping

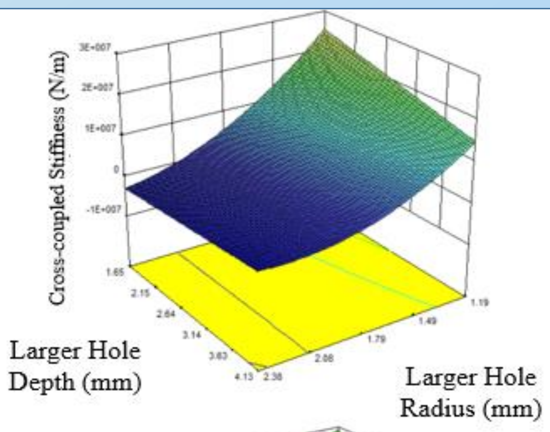
$$\begin{aligned} C_{XX} = {} & 49247.19279 - 1586.43914R_1 \\ & - 6381.29074c - 3882.61700H_1 \\ & - 3907.48899H_2 - 367.81707N_1 \\ & + 54.83858N_2 - 73.17024R_1N_2 \\ & + 633.30984H_1H_2 \end{aligned}$$

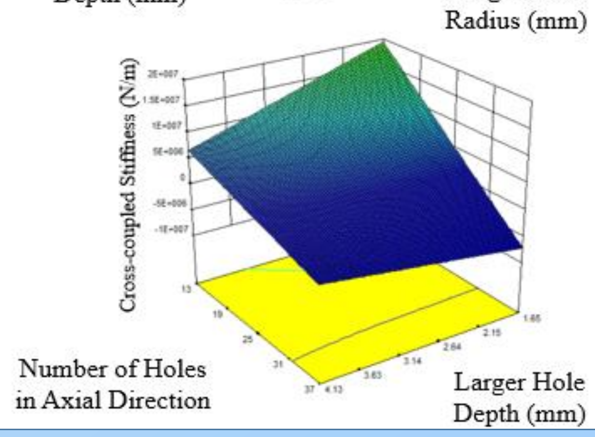




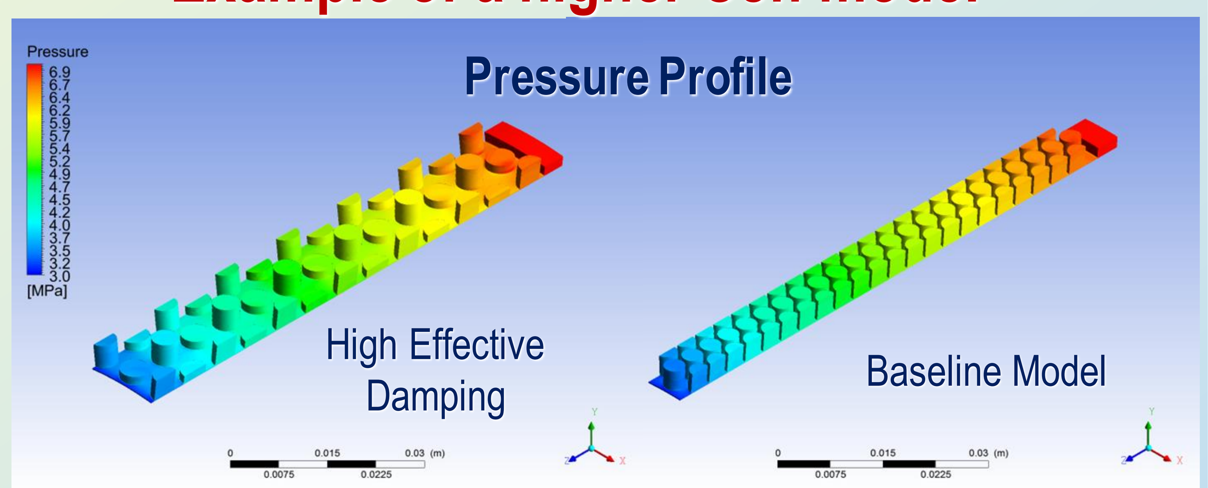
Cross-Coupled Stiffness

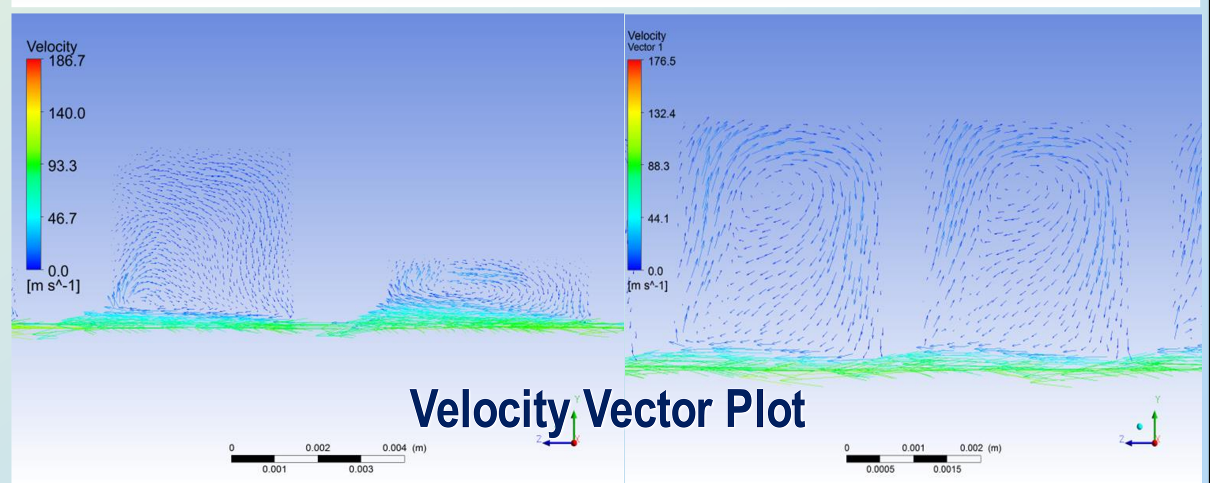
$$\begin{aligned} K_{XY} = {} & 1.74542\times10^{8} - 8.23984\times10^{7}R_1 \\ & - 8.99888\times10^{6}c - 1.72422\times10^{7}H_1 \\ & - 1.94844\times10^{6}H_2 - 1.60199\times10^{6}N_1 \\ & - 1.03254\times10^{5}N_2 + 4.59161\times10^{6}R_1H_1 \\ & + 3.02578\times10^{5}H_1N_1 + 1.42937\times10^{7}R_1^2 \end{aligned}$$





Example of a higher Ceff model





Conclusions

- Alternately arranged hole-patterning has significant effect on dynamic response
- Leakage rate is reduced when the total area of the holes on the stator surface increases
- The radius of larger holes and the number of holes in both axial and circumferential directions are identified as relatively important factors
- The depth of the holes is very important for effective damping
- Using ***different depths*** on an alternately arranged hole-pattern design can significantly affect the dynamic characteristics of the seal
- Results are helpful in designing a seal that can concurrently satisfy constraints on both the leakage rate and the rotor dynamic response while maintaining same design envelope