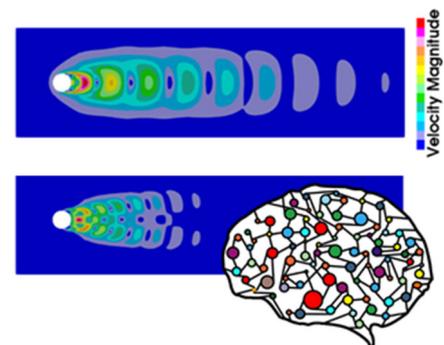


# オンラインセミナー 機械学習と流体シミュレーション

2020年11月13日(金)開催

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# アドバンスソフト株式会社のご紹介

第3事業部 大西陽一

オンラインセミナー「機械学習と流体シミュレーション」

2020年11月13日(金)

アドバンスソフト株式会社



## 会社概要

**名 称** アドバンスソフト株式会社  
(AdvanceSoft Corporation)

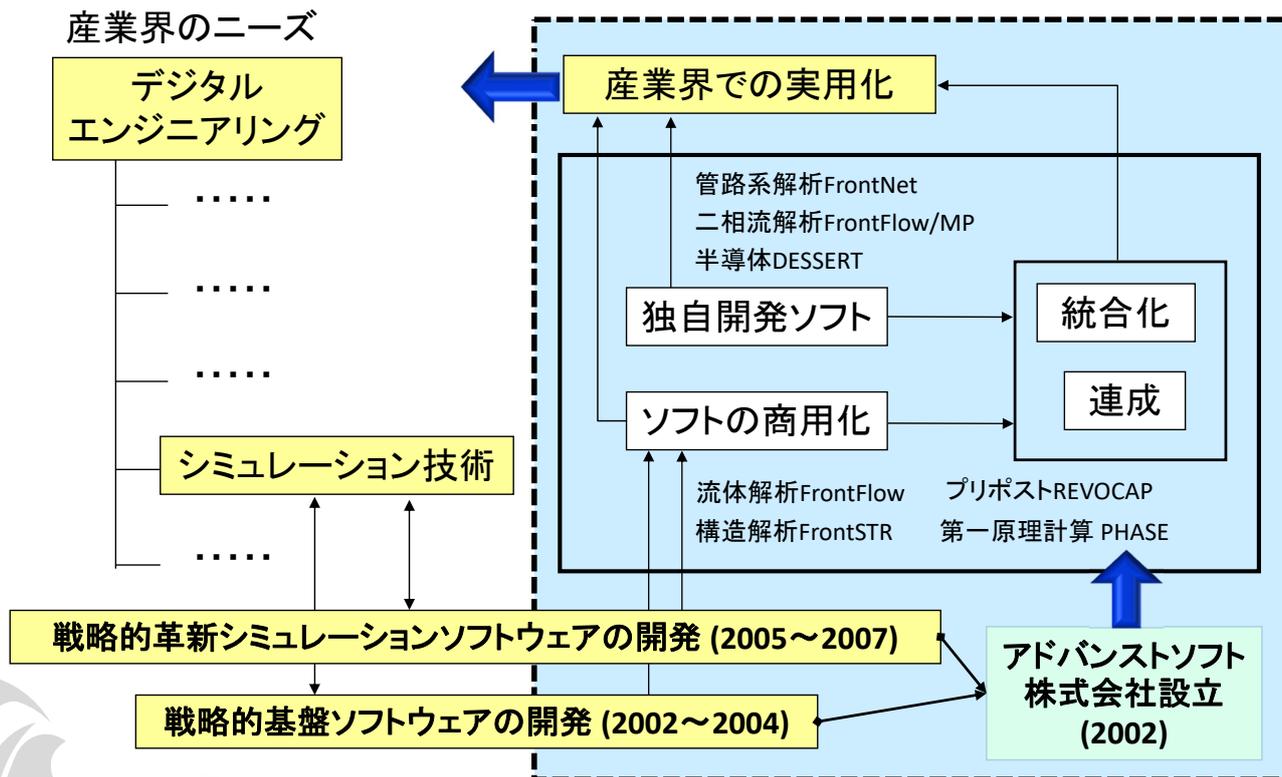
**本 社** 〒101-0062  
東京都千代田区神田駿河台4-3  
新お茶の水ビル17階  
TEL: 03-6826-3970  
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**設 立** 2002年(平成14年)4月24日

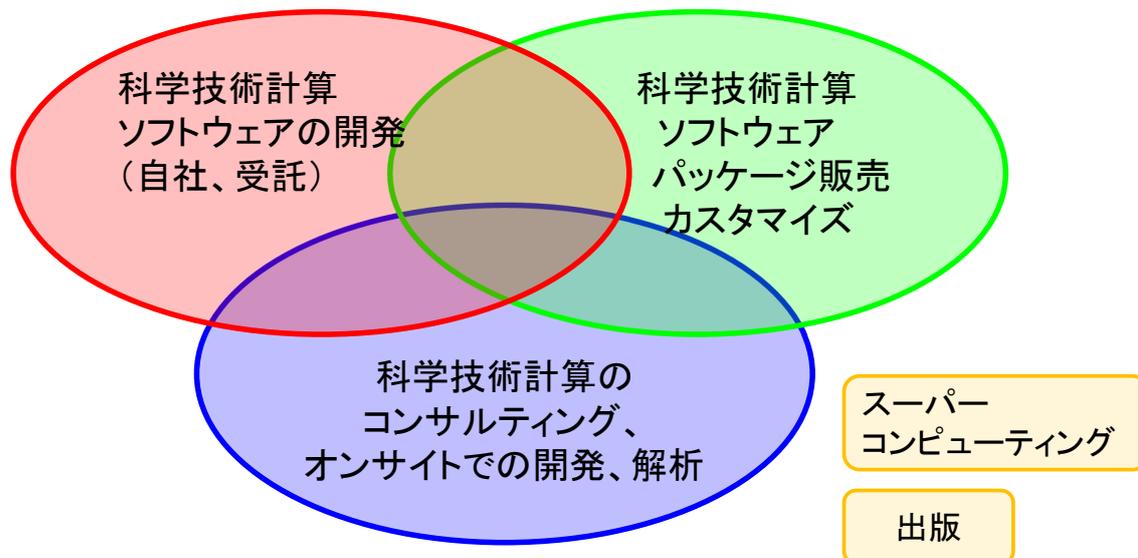
**資本金** 3,724万円

**社員数** 104名(2020年11月13日時点)

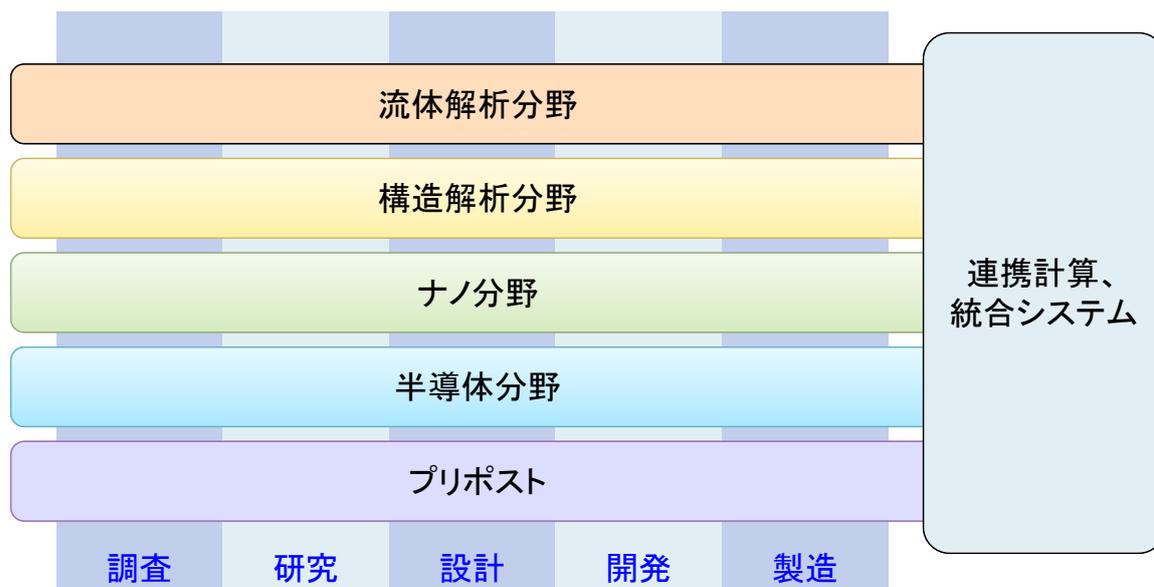
事業部	部	事業内容
第1 事業部	ナノシミュレーション 研究開発センター	先端的なナノシミュレーション事業および関連する国プロを企画・推進
	技術第1部	ナノ材料の第一原理計算ソルバー開発、分子動力学計算・量子化学計算の受託
	技術第2部	プリポストシステム開発、連成システム開発、構造・音響解析などのエンジニアリング、構造解析ソルバーの開発など
	技術第6部	次世代TCADシステムの開発、および半導体解析を中心とした電磁分野
	技術第8部	材料設計統合システムの開発、および、関連する先端的なナノ分野の事業を企画推進
第2 事業部	技術第4部	燃焼・爆轟に係る流体解析ソルバー開発、混相流に係る次世代流体解析システム開発、流体解析ソルバーの受託開発
第3 事業部	技術第3部	乱流、燃焼、化学反応等に係る次世代流体システム開発など
	技術第7部	J-PARCIに係わるプロジェクトの実施、中性子に関する実験支援サービス、AI、制御システム開発およびモデルベース設計に関する事業
第4 事業部	技術第5部	シビアアクシデントおよびPRAを中心とした原子力安全解析
	技術第9部	原子力・エネルギー利用に係る安全性解析など
関西支店		西日本地区での活動拠点。ナノシミュレーションを中心としたサービスを提供
研究 開発 部門	研究開発センター	地球科学を中心とした事業を企画・推進します。
	熱流動エンジニア リングセンター	原子力、管路系、気液二相流等の熱流動エンジニアリング事業
	リスク研究開発 センター	原子力分野に関するPRAを中心としてリスク研究開発に係る事業
総合企画部		コンサルティングサービスの提供 解析サービス、実験支援サービスの提供
営業本部	営業部	お客様窓口



## アドバンスソフトがご提供するサービス



科学技術計算ソフトウェアの開発を基礎とした、  
科学技術計算に関する様々なソリューションをご提供します。



産業の主要な分野のあらゆるフェーズで直面する課題に対し、  
科学技術計算によるソリューションをご提供します。

## 実績

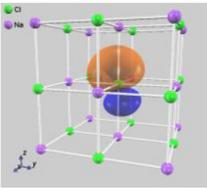
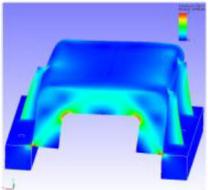
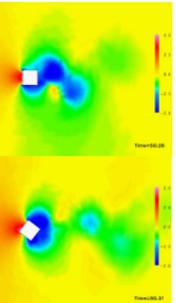
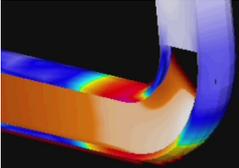
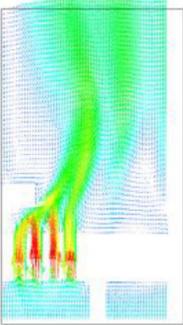
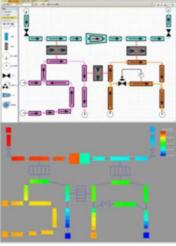
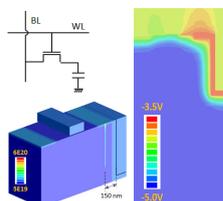
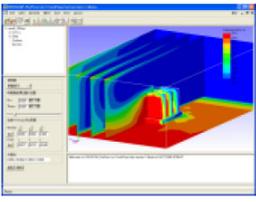
- 当社AIソフトウェアの販売
  - 第一原理計算ソフトウェア Advance/PHASE
  - ニューラルネットワーク分子動力学システム Advance/NeuralMD
  - 深層学習用ツール Advance/iMacle

### 【実績】

1. 深層学習ライブラリKerasを用いた時系列データ予測モデルの作成
2. 機械学習による深度推定モデル実行スクリプトの作成
3. Advance/iMacleによる中性子回折スペクトル解析
4. 自動車モデルパラメータ同定
5. その他にもEV電池や、ナノ系

### 【検討中】

1. 機械学習による設計条件の最適化
2. 最適制御のためのオンライン機械学習ツール設計

<p><b>ナノ</b></p> <p>Advance/PHASE Advance/NanoLabo</p> 	<p><b>構造・音響</b></p> <p>Advance/FrontSTR Advance/FrontNoise</p> 	<p><b>流体</b></p> <p>Advance/FrontFlow/red    Advance/FrontFlow/FOCUS</p>   <p>Advance/FrontFlow/MP</p>  <p>Advance/FrontNetシリーズ</p> 	
<p><b>半導体・光／電磁波</b></p> <p>Advance/TCAD Advance/ParallelWave</p> 	<p><b>プリポスト</b></p> <p>Advance/REVOCAP</p> 		

※上記は主要パッケージを掲載しています。詳細は弊社HP(www.advancesoft.jp)をご参照ください。

## パッケージソフトウェアの解析事例

解析事例Webページをリニューアルしました。

アドバンスソフト 事例集

検索

<http://case.advancesoft.jp>

- ソフトウェア名からだけでなく、産業分野別、解析分野別の検索が可能となりました。
- 最新の事例を掲載しました。今後も逐次最新事例を紹介いたします。

産業分野別	解析分野別
自動車・運輸	流体
材料・化学	爆発・燃焼
産業機械	構造
航空宇宙	振動音響
エレクトロニクス	ナノ・バイオ
建設土木	プリポスト
原子力	半導体デバイス
エネルギー	光・電磁波
環境・防災	

<http://www.facebook.com/advancesoft.jp>

<http://www.youtube.com/user/advancesoft>





## 埋め込み法の最近の進展



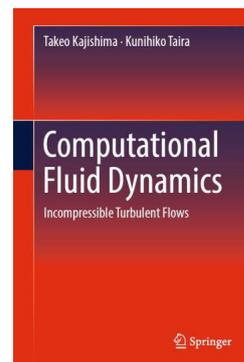
大阪大学 工学研究科 機械工学専攻  
梶島 岳夫

T Kajishima @ Osaka Univ. 

### 話題

#### 前半 埋め込み法の最近の進展

- ▶ 境界の埋め込み
- ▶ 解の埋め込み： 拡散方程式，拡張潤滑理論
- ▶ 埋め込み射影法： すべり境界条件
  - ▶ Kajishima, T. "Immersed boundary/solid method for the numerical simulation of particle-laden flows", → Fluid Dynamics Research, 51-5, 051401, 2019.
  - ▶ 梶島, "Get Immersed!", ながれ, 37-6, 503-506, 2018. (日本流体力学会ホームページから参照可 [https://www.nagare.or.jp/download/noauth.html?d=37-6\\_tokubetu.pdf&dir=75](https://www.nagare.or.jp/download/noauth.html?d=37-6_tokubetu.pdf&dir=75))



#### 後半 深層強化学習による翼形状パラメータの最適化の試み (岡林希依)

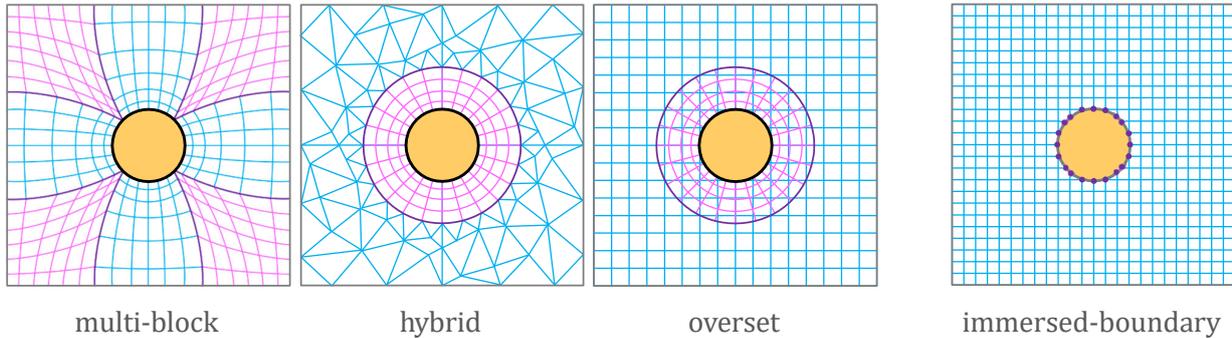
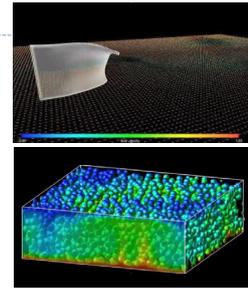
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## 計算格子

- ▶ 複雑形状境界
- ▶ 移動境界
  - ▶ 流体-構造 連成
  - ▶ 固体-流体 二相流

- ➔ 柔軟構造物
- ➔ 多体問題

Re-mesh becomes difficult.



multi-block

hybrid

overset

immersed-boundary

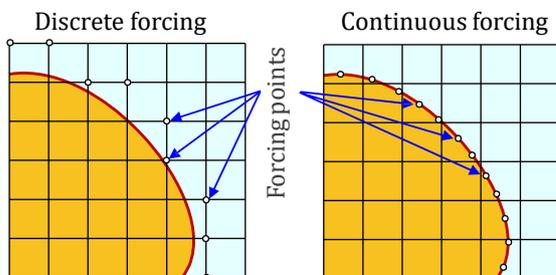
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## 埋め込み法

### ▶ Immersed boundary method

- ▶ 高解像度
  - ▶ 複雑形状境界流れ, 流体構造連成解析, 透過膜

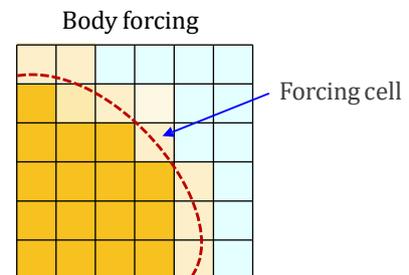


- ▶ Ikeno et al. (2007)
- ▶ Sato et al. (2013)
- ▶ Miyauchi. (2015)

### ▶ Immersed solid method

(体積力型埋め込み境界法)

- ▶ 高効率
  - ▶ 固体流体二相乱流, 固液二相伝熱



- ▶ Kajishima et al. (2001, 2002)
- ▶ Takeuchi et al. (2010)
- ▶ Gu et al. (2018)

T Kajishima @ Osaka Univ.



## 解の置換

### ▶ 解強制置換法

Fujii, K., "Unified Zonal Method Based on the Fortified Solution Algorithm", J. Comput. Phys., 118, 92-108, 1995.

$$\frac{Q^{n+1} - Q^n}{\Delta t} + \nabla \cdot \mathbf{F} = \chi (Q_F - Q^{n+1})$$

- ▶ 相対的に移動する複数の格子の間で解を伝達例) 列車とともに移動する格子, トンネル内に固定された格子

### ▶ 体積力型埋め込み境界法

Kajishima, T. & Takiguchi, S. "Interaction between particle clusters and fluid turbulence", Int. J. Heat and Fluid Flow, 23-5, 639-64, 2002.

$$\frac{\mathbf{u}^{n+1} - \mathbf{u}^n}{\Delta t} + \nabla \cdot \mathbf{H} = \alpha \frac{\mathbf{u}_p - \hat{\mathbf{u}}_f}{\Delta t}$$

$$\mathbf{u} = \alpha \mathbf{u}_p + (1 - \alpha) \mathbf{u}_f$$

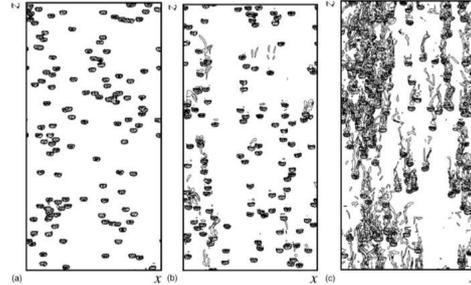


Fig. 5. Instantaneous flow field, including 128 falling particles, visualized by  $\nabla \cdot \mathbf{p}$  projected in the horizontal (top row) and vertical (bottom row) planes. (a)  $Re_p = 100$ , (b)  $Re_p = 200$  and (c)  $Re_p = 400$ .

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## 高濃度固液二相対流伝熱

### ▶ 支配方程式

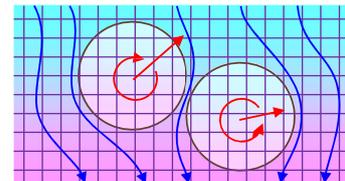
- ▶ 流れ場 (非圧縮ニュートン流体) → Eulerian
- ▶ 固体粒子 (剛体球) → Lagrangian
- ▶ 温度場 → Eulerian

### ▶ カプリング

- ▶ 固液の運動量交換 → 体積力型埋め込み境界法
  - ▶ Kajishima et al. (2001), Takeuchi et al. (2010)
- ▶ 固体間相互作用 → DEM Tsuji et al. (1993)
- ▶ 固液界面の熱伝達モデル Takeuchi et al. (2013)

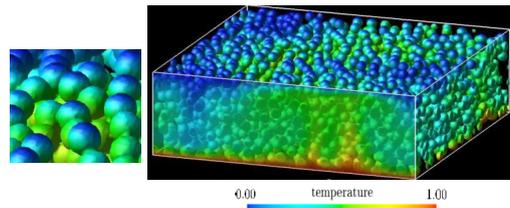
### ▶ 固液二相伝熱に特有な現象

- ▶ 逆温度勾配
- ▶ 振動モード
- ▶ 対流反転



Fixed Cartesian grid

$Ra = 10^5$ ,  $E_p = 10^7$ ,  
 $N_p = 3087$ ,  $\phi = 30.8\%$ ,  $\lambda_s/\lambda_f = 1$



Gu, Kondo, Takeuchi & Kajishima, ICMF-2016, Firenze

T Kajishima @ Osaka Univ.



## 非圧縮流れに対する射影法

### ▶ 射影法（部分段階法）

Perot, J.B., "An analysis of the fractional step method", J. Comput. Phys. 108, 51-58 (1993)

$$\frac{\mathbf{u}^{n+1} - \mathbf{u}^n}{\Delta t} = -\mathcal{G}P^{n+1} + \mathbf{A}$$

$$\mathcal{D}\mathbf{u}^{n+1} = 0$$

### ▶ マトリックス表示

$$\begin{bmatrix} I & \Delta t\mathcal{G} \\ \mathcal{D} & 0 \end{bmatrix} \begin{bmatrix} \mathbf{u}^{n+1} \\ P^{n+1} \end{bmatrix} = \begin{bmatrix} \mathbf{u}^n + \Delta t\mathbf{A} \\ 0 \end{bmatrix}$$

### ▶ LU分解

$$\begin{bmatrix} I & 0 \\ \mathcal{D} & -\Delta t\mathcal{D}\mathcal{G} \end{bmatrix} \begin{bmatrix} \mathbf{u}^* \\ P^* \end{bmatrix} = \begin{bmatrix} \mathbf{u}^n + \Delta t\mathbf{A} \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} I & \Delta t\mathcal{G} \\ 0 & I \end{bmatrix} \begin{bmatrix} \mathbf{u}^{n+1} \\ P^{n+1} \end{bmatrix} = \begin{bmatrix} \mathbf{u}^* \\ P^* \end{bmatrix}$$

埋め込むタイミングは？

- Projectionの前 → 境界条件が反映されない
- Projectionの後 → 連続の式が破綻する

Kajishima, T.

"Immersed boundary/solid method for the numerical simulation of particle-laden flows", Fluid Dynamics Research, 51-5, 051401, 2019.

T Kajishima @ Osaka Univ.



## 非圧縮流れに対する射影法

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$$\begin{bmatrix} I & \Delta t\mathcal{G} \\ 0 & I \end{bmatrix} \begin{bmatrix} \mathbf{u}^{n+1} \\ P^{n+1} \end{bmatrix} = \begin{bmatrix} \mathbf{u}^* \\ P^* \end{bmatrix}$$

### ▶ 埋め込み境界射影法

Taira, K. & Colonius, T., "The immersed boundary method: A projection approach", J. Comput. Phys. 225, 2118-2137 (2007)

$$\left. \begin{array}{l} \text{格子点} \quad \frac{\mathbf{u}^{n+1} - \mathbf{u}^n}{\Delta t} = -\mathcal{G}P^{n+1} + \mathbf{A} + \mathcal{H}\mathbf{f}^{n+1} \\ \text{境界点} \quad \mathbf{u}_b^{n+1} = \mathcal{E}\mathbf{u}^{n+1} \end{array} \right\}$$

### ▶ マトリックス表示

$$\begin{bmatrix} I & \Delta t\mathcal{G} & -\Delta t\mathcal{H} \\ \mathcal{D} & 0 & 0 \\ \mathcal{E} & 0 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{u}^{n+1} \\ P^{n+1} \\ \mathbf{f}^{n+1} \end{bmatrix} = \begin{bmatrix} \mathbf{u}^n + \Delta t\mathbf{A} \\ 0 \\ \mathbf{u}_b^{n+1} \end{bmatrix}$$

### ▶ Taira-Colonius

$$\begin{bmatrix} I & \Delta t\mathcal{Q} \\ \mathcal{Q}^T & 0 \end{bmatrix} \begin{bmatrix} \mathbf{u}^{n+1} \\ \mathbf{L}^{n+1} \end{bmatrix} = \begin{bmatrix} \mathbf{u}^n + \Delta t\mathbf{A} \\ \mathbf{R} \end{bmatrix}$$

$$\mathbf{L}^{n+1} = [P^{n+1}, \mathbf{f}^{n+1}]^T$$

T Kajishima @ Osaka Univ.



## 理論解の埋め込み

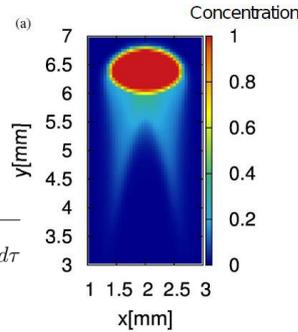
- ▶ 高シュミット数の濃度境界層の拡散方程式の解の埋め込み

$$\frac{\partial c}{\partial t} - \left( n \frac{\partial \ln s}{\partial t} \right) \frac{\partial c}{\partial n} = D \frac{\partial^2 c}{\partial n^2}$$

$$\text{where } s = s(\xi, \eta, t) = \left| \frac{\partial r_s}{\partial \xi} \times \frac{\partial r_s}{\partial \eta} \right|$$

$$\Rightarrow \frac{c}{c_0} = \operatorname{erfc} \frac{n}{\delta(\xi, \eta, t)}$$

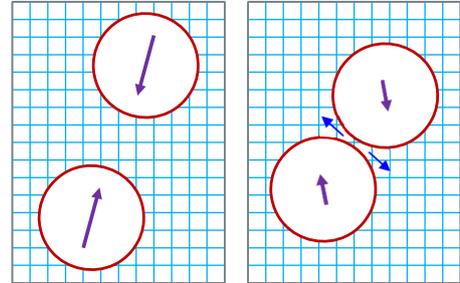
$$\text{where } \delta(\xi, \eta, t) = \sqrt{4D \int_0^t \left[ \frac{s(\xi, \eta, \tau)}{s(\xi, \eta, t)} \right]^2 d\tau}$$



$$S_C = 100, \quad \operatorname{Re} = 30 \\ D/\Delta_x = 20$$

足立・大森・梶島, 機論 82(839) 16-00079, 2016

- ▶ 衝突・反発, 接触
- ▶ 狭隘流路 (スクイズ流れ)



→ 潤滑理論解の埋め込み

T Kajishima @ Osaka Univ. 

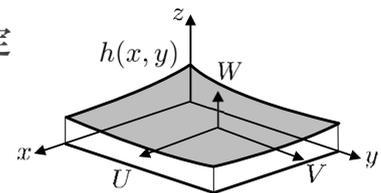
## Reynoldsの潤滑方程式

- ▶ 薄層近似 (Hele-Shaw流れ)

$$\frac{\partial p}{\partial x} = \mu \frac{\partial^2 u}{\partial z^2}, \quad \frac{\partial p}{\partial y} = \mu \frac{\partial^2 v}{\partial z^2}, \quad \frac{\partial p}{\partial z} = 0$$

- ▶ 局所的に  $p(x, y)$  を与えて Couette-Poiseuille 流れを仮定

$$\left. \begin{aligned} \bar{u} \left( = \frac{1}{h} \int_0^h u dz \right) &= \frac{U}{2} - \frac{h^2}{12\mu} \frac{\partial p}{\partial x}, \\ \bar{v} \left( = \frac{1}{h} \int_0^h v dz \right) &= \frac{V}{2} - \frac{h^2}{12\mu} \frac{\partial p}{\partial y} \end{aligned} \right\}$$



- ▶ 連続の式  $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$  の各項を膜厚間  $z = 0 \sim h(x, y)$  で積分

$$\frac{\partial}{\partial x} \left( h^3 \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left( h^3 \frac{\partial p}{\partial y} \right) = 6\mu \left[ \frac{\partial(hU)}{\partial x} + \frac{\partial(hV)}{\partial y} \right] - 12\mu \left( U \frac{\partial h}{\partial x} + V \frac{\partial h}{\partial y} - W \right)$$

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## 拡張潤滑理論

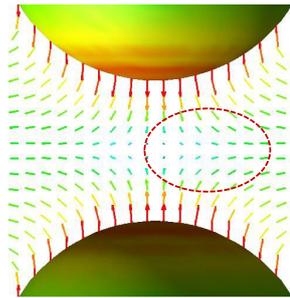
### ▶ 薄層近似の前提

$$(h \ll L, dh/dx \sim 0, dh/dy \sim 0, dp/dz \sim 0)$$

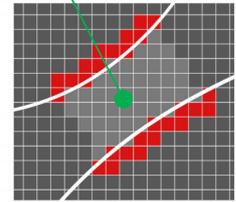
が破綻する領域まで拡張

$$\left. \begin{aligned} \frac{\partial p}{\partial x} &= \frac{1}{\mu} \frac{\partial^2 u}{\partial z^2} \\ \frac{\partial p}{\partial y} &= \frac{1}{\mu} \frac{\partial^2 v}{\partial z^2} \\ \frac{\partial p}{\partial z} &= \frac{1}{\mu} \frac{\partial^2 w}{\partial z^2} \end{aligned} \right\} \Leftrightarrow \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Takeuchi, S. & Gu, G., "Extended Reynolds lubrication model for incompressible Newtonian fluid" *Physical Review Fluids*, 4(11) 114101 (2019)



格子解像度が不足する領域を判断して理論解を埋め込み、周囲と接続する

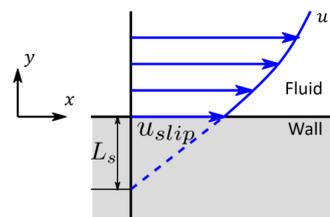


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## すべり境界条件に対する埋め込み境界射影法

### ▶ Continuous forcing approach considering Navier boundary condition

$$\underbrace{u - u^B}_{u_{slip}} = \mathcal{L}_s \frac{\partial u}{\partial y} \quad \begin{array}{l} u_{slip}: \text{すべり速度} \\ L_s: \text{すべり長さ} \end{array}$$



### ▶ 境界条件の演算子表現

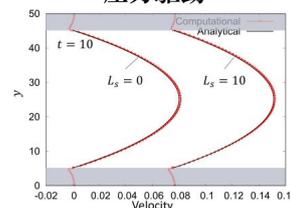
$$(\nabla \mathbf{u})^T : \mathbf{nt} = \frac{\partial u_n}{\partial x_t} - \kappa u \quad , \quad \nabla \mathbf{u} : \mathbf{nt} = \frac{\partial u_t}{\partial x_n} \text{より}$$

$$(1 + L_s \kappa) u_t - L_s \frac{\partial u_t}{\partial x_n} = u^B + L_s \frac{\partial u_n^B}{\partial x_t}$$

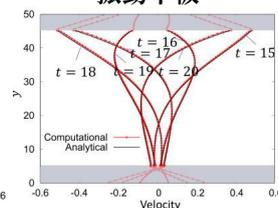
藤井・大森・梶島, 日本機械学会  
第98期流体工学部門講演会(2020) OS06-13

### 平板間流れ

#### 圧力駆動



#### 振動平板



T Kajishima @ Osaka Univ.

# Modal Analysis of Fluid Flows

Introduction, Applications, and Outlook

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AdvanceSoft Online Seminar: 2020/11/13 (Friday)

## Acknowledgements

Students, postdocs, and colleagues:



and many other students and colleagues

Sponsors:



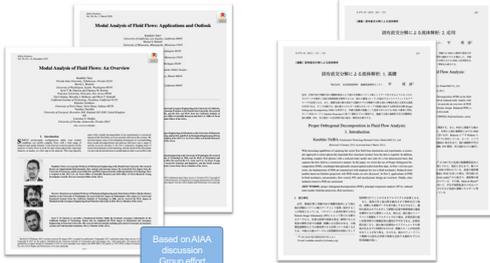
## References

### Modal Analysis

- Taira et al., AIAA J 2017 (Overview)
- Taira et al., AIAA J 2020 (Applications/Outlook)

### Proper Orthogonal Decomposition

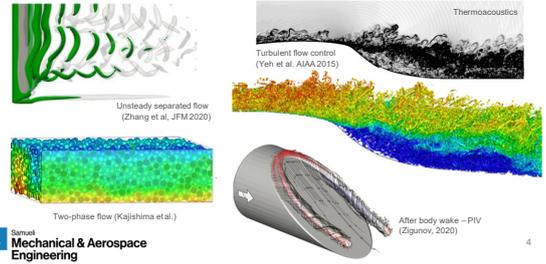
- 平, ながれ 2011 (基礎)
- 平, ながれ 2011 (応用)



Based on AIAA discussion Group effort

## Current status of our field

- We are capable of computationally and experimentally analyzing most flow fields. We know how to perform CFD and experiments!
- Enhancements in computational resources (processors, memory, hard drive, data transfer, etc.) have enabled us to examine increasingly complex high-dimensional flow problems. The same can be said about experimental diagnostics.



## Starting Point

As we analyze fluid flows, we have the following:

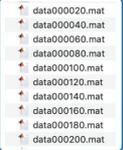
Navier-Stokes equations

$$\frac{\partial \mathbf{q}}{\partial t} = \mathbf{f}(\mathbf{q})$$

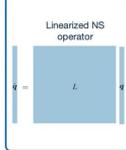
CFD solvers



BIG DATA



BIG OPERATOR



Questions:

- How can we use big data and big operator to enhance our understanding fluid flows.
- Can we model/predict the dominant behavior of fluid flows?

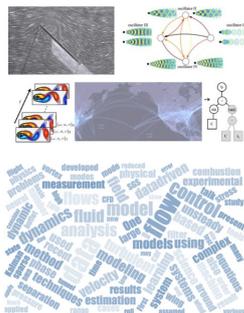
## Learning Physics from Data

- Analysis of data becoming increasingly difficult due to its growing size ("Big Data").
- Can we go beyond traditional statistical analysis and visualization?
- Can we use discrete operators from CFD solvers?
- Super exciting time in research with explosion of new ideas in data science!



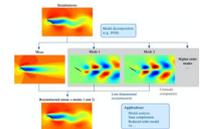
## Data Science\*

- Data science is a "concept to unify statistics, data analysis, machine learning and their related methods" in order to "understand and analyze actual phenomena" with data. It employs techniques and theories drawn from many fields within the context of mathematics, statistics, computer science, and information science.
- Jim Gray imagined data science as a "fourth paradigm" of science (empirical, theoretical, computational and now data-driven) and asserted that "everything about science is changing because of the impact of information technology" and the data deluge.



## Modal Analysis

INTRODUCTION



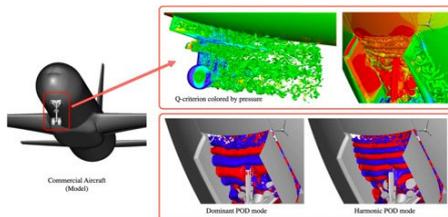
## Analysis of Unsteady Fluid Flows

- Is there hope to tackle complex problems with a large range of scales?
- We are generally interested in the "dominant" behavior of the flows.
- Our eyes can be very effective in identifying structures!



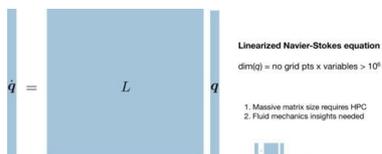
## From Low to High Re

- Applications of modal analysis has often been limited to low-Re flows and low-to-moderate dimensional data sets
- However, even at high-Re flows, physical insights can be obtained\*
- We generally seek **only the dominant modes**...



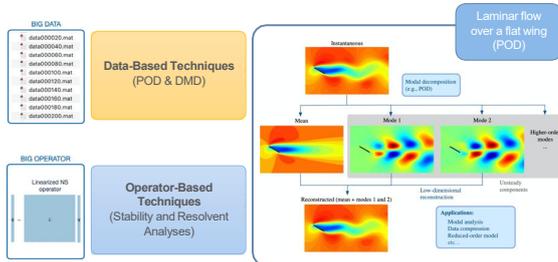
## Modal Analysis

- Unsteady fluid flows exhibit complex dynamics with nonlinear, high-dimensional, and multi-scale properties.
- Extraction of essential dynamics is critical for understanding and controlling unsteady flows.
- Modal analysis techniques can extract dominant modes, compress data, identify instabilities, and reveal input/output properties
- Most techniques are based on eigenvalue and singular value analyses



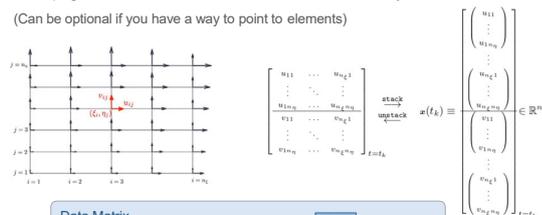
## Modal Analysis

- Modal analysis technique can identify dominant spatial structures from the flow field.
- Applications: analysis, data compression, modeling, control, design optimization



## Data Preparation

- In our analysis, we view each snapshot of the instantaneous flow field as a vector
- Reshaping our flow field data into a vector can facilitate our analysis
- (Can be optional if you have a way to point to elements)



Data Matrix

$$X = [x(t_1) \ x(t_2) \ \dots \ x(t_m)] \in \mathbb{R}^{n \times m}$$

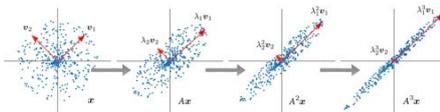
## Eigenvalue Decomposition

- Eigenvalue decomposition reveals the dominant directions that a linear operator acts along.

$$Av = \lambda v$$

$$A = V\Lambda V^{-1}$$

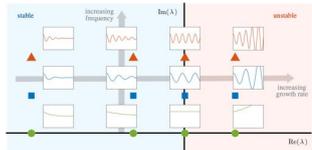
A must be a square matrix



$$x \notin \mathcal{L}x$$

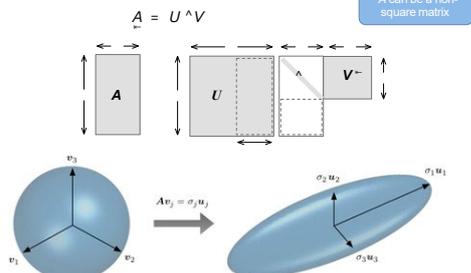
$$x(t) = \exp(Lt)x(t_0)$$

$$= V \exp(\Lambda t) V^{-1} x(t_0)$$



## Singular Value Decomposition

- Singular value decomposition finds the basis vectors in the domain and range of the operator and the gain that relates them.



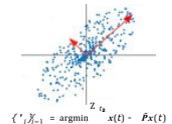
## Proper Orthogonal Decomposition

- POD reveals the best basis functions (modes) to capture the fluctuations in the flow field.
- POD modes are orthogonal (cf., Fourier analysis)

$$u(t, x) = \sum_j \mathbf{a}_j(t) \cdot \mathbf{j}(x)$$

Unsteady flow field (mean removed)

Temporal POD coefficients/modes



INPUT: Snapshots of scalar (e.g., pressure, temperature) or vector (e.g., velocity, vorticity) field compiled as data matrix X.

OUTPUT: Set of orthogonal POD modes  $\mathbf{j}(x)$ , and the corresponding temporal coefficients  $\mathbf{a}_j(t)$ , and energy levels  $\lambda_j$  arranged in decreasing order.

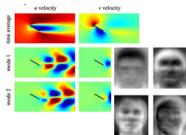
- (1) POD is also known as PCA (Principal Component Analysis) and KL (Karhunen-Loeve) expansion.
- (2) L2 optimal modes; captures kinetic energy optimally (for velocity field)
- (3) POD modes can be found from SVD or eigenvalue decomposition

## Proper Orthogonal Decomposition

Algorithm:

- Prepare data matrix  $X = [x(t_1) \ x(t_2) \ \dots \ x(t_m)] = R^{n \times m}$
- Solve the eigenvalue problem  $XX^T u_j = \lambda_j u_j$
- Alternatively, one can solve  $X^T X u_j = \lambda_j u_j$  (Method of snapshots\*)

- POD is also known as PCA (Principal Component Analysis)
- L2 optimal modes; captures kinetic energy optimally (for velocity field)
- POD modes can be found from SVD or eigenvalue decomposition
- Interesting fact: Eigenface analysis\*\* was published by Sirovich around the same time.



## Dynamic Mode Decomposition

- DMD reveals the time-evolution properties of the data
- Uncovers dynamical modes with characteristic frequencies and growth/decay rates.
- Finds eigendecomposition of  $A$  that approximates the nonlinear dynamics

$$x(t_{k+1}) = f(x(t_k)) \doteq Ax(t_k)$$

nonlinear linear  
Linear approximation of nonlinear dynamics

**INPUT:** A set of snapshot pairs from fluids experiments or simulations, where the two snapshots in each pair are separated by a constant interval of time.

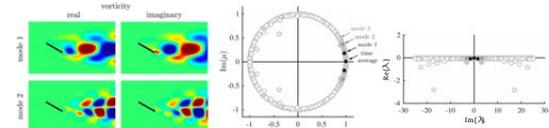
**OUTPUT:** DMD eigenvalues and modes. The modes are spatial structures that oscillate and/or grow/decay at rates given by the corresponding eigenvalues.

- Closely related to global stability analysis and Koopman analysis.
- Discrete approximation to the Koopman analysis.
- Modes are complex-valued and not orthogonal
- No need to remove mean flow (cf. POD analysis)

## Dynamic Mode Decomposition

Algorithm:

- Prepare two data matrices  $X_1 = [x(t_1), x(t_2), \dots, x(t_m)]$   
 $X_2 = [x(t_2), x(t_3), \dots, x(t_{m+1})]$
- Assume  $X_2 = AX_1$  and use SVD to solve an eigenvalue problem  $X_1 = U^A V^T$ ,  $A = U^A X_2 V^A^{-1} = U^A A U$ ,  $A \bar{v}_k = \mu_k \bar{v}_k$
- Find the DMD modes and DMD eigenvalues (growth rates/frequencies)  $v_k = \frac{1}{\mu_k} X_2 V^A \bar{v}_k$ ,  $k = \frac{1}{\Delta t} \log(\mu_k)$



## Stability Analysis

- (Linear global) stability analysis reveals the instability property of the dynamics about a selected base state (equilibrium). Provides the spatial instability modes and the growth rate/frequencies.

$$\frac{\partial q}{\partial t} = F(q) \xrightarrow{\text{Linearization about base state}} \frac{\partial q^0}{\partial t} = Lq^0$$

$$q(x, t) = \bar{q}(x) + q^0(x, t)$$

- The dominant dynamics of the instability is captured by looking for the most unstable eigenmodes. Solve the eigenvalue problem.

$$q^0(x, t) = q^0(x) e^{\lambda t} \quad Lq^0 = \lambda q^0$$

eigenvector (instability mode)  
eigenvalue

$$\lambda = \text{Re}(\lambda) + i \text{Im}(\lambda) \quad e^{\lambda t} = e^{\text{Re}(\lambda)t} [\cos(\text{Im}(\lambda)t) + i \sin(\text{Im}(\lambda)t)]$$

**INPUT:** Steady base flow (stable or unstable). Discrete linear NS operators (or a code).

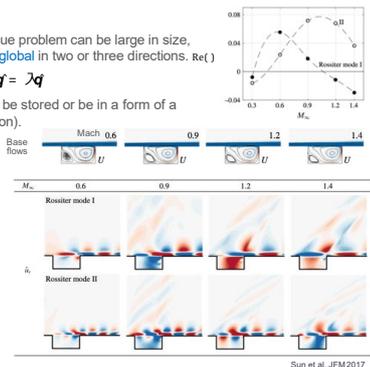
**OUTPUT:** Stability modes (eigenvectors) and growth rates/frequencies (eigenvalues).

## Stability Analysis

Algorithm

- For fluid flows, the eigenvalue problem can be large in size, especially if the problem is global in two or three directions.  $\text{Re}(\lambda)$
- The linear NS operator can be stored or be in a form of a code (matrix-vector operation).

- Analyzes the initial-value problem for linear perturbation.
- Stable equilibrium/base flow is easy to find. Unstable equilibrium can be difficult to find especially for high Re flow (see Newton solvers and selective frequency damping).



## Resolvent Analysis

- Resolvent analysis reveals the linear input-output relationship between forcing and response about a base state.
- Analogous to stability analysis but with harmonic forcing (sustained oscillation).

$$\frac{\partial q^0}{\partial t} = Lq^0 + f^0 \quad q(x, t) = \bar{q}(x) + q^0(x, t)$$

- For sustained forcing and response, we can use Fourier representation

$$q^0(x, t) = q^0(x) e^{i\omega t} \quad i\omega q^0 = Lq^0 + f^0$$

$$f^0(x, t) = f^0(x) e^{i\omega t}$$

$$q = Hf \quad H = [i\omega I - L]^{-1} C^{n \times n}$$

Resolvent operator

- Resolvent analysis is closely related to pseudospectral analysis.
- Assumes statistically stationary flow to use Fourier expansion.
- Can use time-average flow for base flow, which expands the applicability to turbulent flows.

## Resolvent Analysis

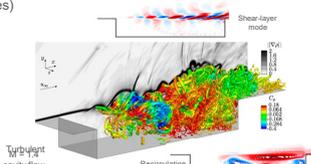
**INPUT:** A real frequency  $\omega$  and a linear NS operator about a base state.

**OUTPUT:** An ordered set of forcing and response modes and the amplification factor.

Algorithm

- Perform singular value decomposition of the resolvent operator  $H = Q^A F^{-1}$  (Both forcing and response modes are orthogonal set of modes)
- $F$ : forcing modes (right singular vectors) and  $Q$ : response modes (left singular vectors)
- $\Sigma$ : amplification/gain (singular values)

- Leading mode with largest gain is generally sought.
- Resolvent analysis is analogous to transfer function in modern control theory.
- Essentially the only (operator-based) modal analysis technique that can handle turbulent flows.



## Reduced-Order Modeling (ROM)

- The full governing equations can be modeled by using the dominant modes found from modal analysis.

$$u(t, x) = u^0(x) + \sum_{j=1}^r \bar{a}_j(t) \bar{v}_j(x)$$

Reduced to  $r \ll n$  equations for temporal coefficients

$$u = f(u) \Rightarrow \sum_{j=0}^r \bar{a}_j \sum_{k=0}^r \bar{v}_k = hf, \quad \dot{\bar{a}} = h f, \quad \bar{a} = h f, \quad \bar{a} = h f$$

- Expand the field variable (e.g., velocity) up to  $r$  modes.
- Substitute expansion into NS equation and take inner product (Galerkin projection).
- Orthogonality of modes facilitates the development of ROM (e.g., POD modes)
- Constraints satisfied by the flow are satisfied by the modes (e.g., incompressibility, no-slip)

$$\frac{d\bar{a}}{dt} = \sum_{j=0}^r F_{ij} \bar{a}_j + \sum_{j=1}^r G_{ijk} \bar{a}_j \bar{a}_k$$

$$F_{ij} = \text{Re}^{-1} \langle v_j, r^2 \rangle_j$$

$$G_{ijk} = h \langle v_i, v_j \cdot r \cdot v_k \rangle$$

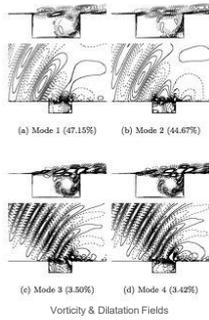
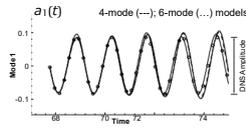
span  $\{v_1, \dots, v_r\}$

## Example: Cavity Flow ROM

Example: 2D cavity flow

- $M = 0.6$ ,  $Re_q = 68.5$
- Nonlinear Galerkin model
- Basis: POD modes

$$\frac{da_i}{dt} = \sum_{j=0}^{X'} F_{ij} a_j + \sum_{j=1}^{X'} \sum_{k=0}^{X'} G_{ijk} a_j a_k$$

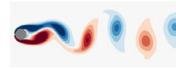


Vorticity & Dilatation Fields

Rowley et al, Physica D, 2004.

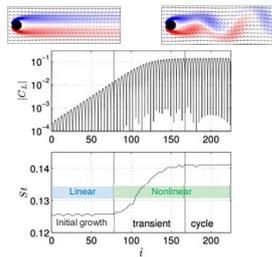
## Proper Orthogonal Decomposition & Dynamic Mode Decomposition

EXAMPLE: CYLINDER FLOW



## Data Preparation

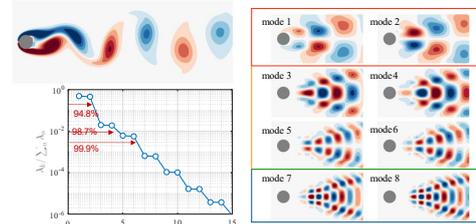
- To perform POD and DMD, we need instantaneous flow field data (snapshots)
- We must carefully choose the spatial domain and temporal coverage. Analysis needs to be provided with physically important data.
- Uniform grid vs non-uniform grid/unstructured grid setup.
- Need sufficient points per period (Nyquist rule). Temporal compression possible<sup>1</sup>.
- Example: cylinder wake development<sup>2</sup>
  1. Initial growth (linear)
  2. Transient (nonlinear)
  3. Limit cycle (nonlinear)



<sup>1</sup>Candès, Romberg & Tao, 2006; Donoho, 2006.  
<sup>2</sup>Chen et al, J Nonlin Sci, 2012.

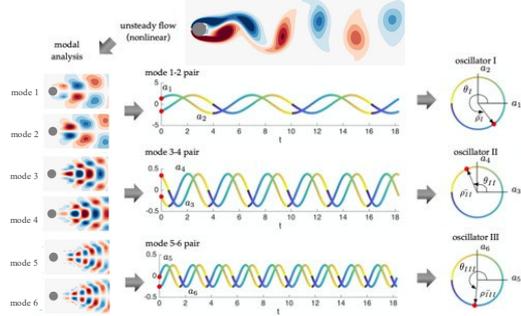
## POD Analysis of Cylinder Flow

- Let us consider a simple 2D laminar cylinder flow ( $Re = 100$ )
- Clean periodic von Karman vortex shedding.



Notes: (1) Modes are orthogonal and real-valued  
(2) Oscillatory modes appear in pairs  
(3) Generally associated with multiple frequencies

## Oscillatory Motion with POD modes



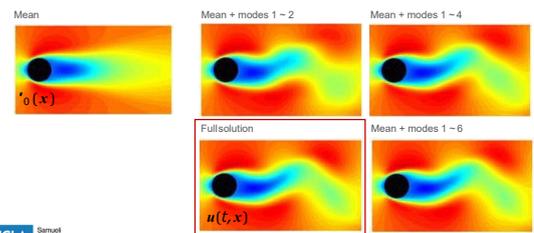
Nair et al, PRE 2018

## Reconstructed Flow

- If we store the POD modes, we can compress the data needed to represent the overall flow field. All you would need to know is the amplitude of the modes at each time.

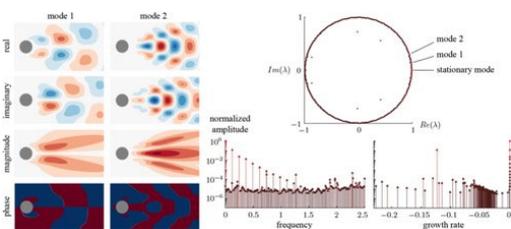
$$u(t, x) = \bar{u}_0(x) + \sum_{j=1}^{X'} a_j(t) \phi_j(x)$$

U velocity



## Dynamic Mode Decomposition

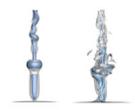
- Analogously, we can study the flow field with DMD. Each mode is distinctly associated with each frequency and growth rate.



Notes: (1) Modes are not orthogonal  
(2) Stationary mode = time-average flow  
(3) Modes are complex-valued

## Dynamic Mode Decomposition

EXAMPLE: ANALYSIS AND CONTROL OF VORTEX IN PUMP SUMP



## Water Resource Management

- Removal of water in a robust manner for a range of operating conditions is critical for management of water resource and safety of the residents.
- Emergence of vortices in pump sumps can be detrimental to operation of pumps and problematic for certification.



図1 武蔵水路 (出典: (左) 水資源機構 武蔵水路改築建設所 刊)



Eto, JSME 2014; Fujii et al., Ebara Eng Rev, 2016

## Model Problem Selection

The analysis of the full-scale flow is too complex to analyze. We hence seek a model flow that possess the important flow dynamics.

Goal: to develop a flow control technique that modifies the profile of the pump sump vortex (core pressure alleviation/increase)

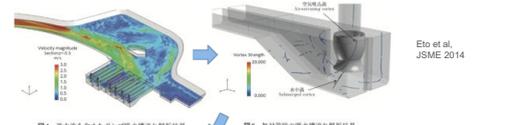
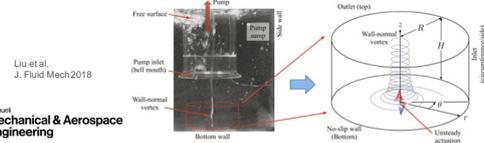


図4 渦糸を含むポンプ水筒内流れの可視化 (ポンプの自然な流れ)

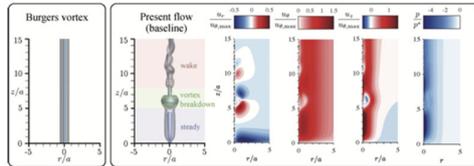
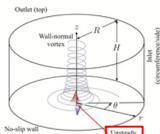
Eto et al., JSME 2014



Liu et al., J. Fluid Mech 2018

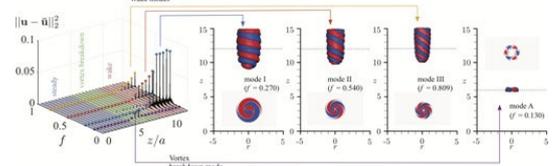
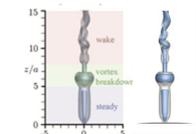
## Active Flow Control

- Introduce unsteady blowing (injection of water) from the bottom wall to alter the vortex profile.
- Aim to increase the pressure profile to spread the vortex core radially.
- Prevent air/debris accumulation at the core
- Pump sump vortex model similar to Burgers vortex



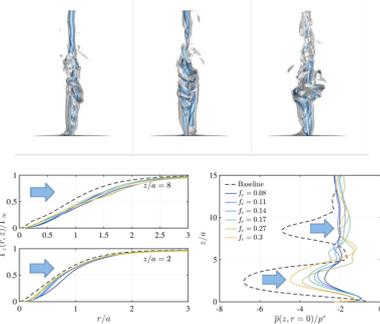
## Unsteady Vortex Dynamics

- The wall-normal vortex exhibits rich dynamics with multiple instabilities.
- To understand dynamics, we perform DMD on the flow field data.
- We identify swirling modes I, II, III and breakdown/bursting mode A.



## Flow Control

- We introduce unsteady blowing near the identified frequencies at the vortex center.
- Forcing input successful in widening the core profile and increasing the core pressure
- Also tested robustness of the control setup (not shown)



## Resolvent Analysis

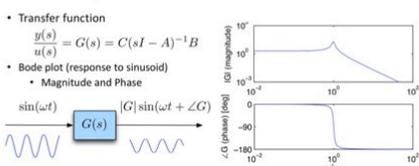
EXAMPLE: SEPARATED FLOW OVER AN AIRFOIL



## Separation Control



Lift Enhancement/Drag Reduction?

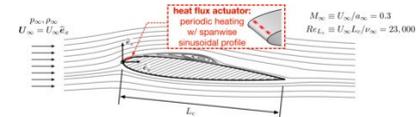


- High-dimensional flow dynamics ( $10^6$  DOF) with nonlinearity

## Problem Setup

Goal: To develop physics-based design of active technique for separation control.

- Turbulent flow over a NACA 0012 airfoil at  $\alpha = 9^\circ$  and  $Re = 23,000$ .
- Compressible LES performed at  $M = 0.3$  in spanwise periodic setting.

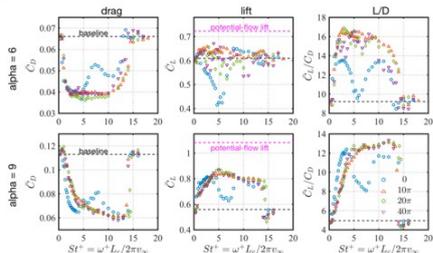


- Actuator model (heat flux  $BC_2^+$ ):  $\phi = \hat{\phi} \sin(2\pi f^+ t) \cos(k_z^+ z)$
- Control parameters:  $St^+ = \Gamma^+ L_c \sin \alpha / U_\infty$  &  $k_z^+ L_c$
- Normalized forcing power:  $E^+ = \frac{\Phi}{\frac{1}{2} \rho_\infty U_\infty^2 \cdot AU_\infty} = 0.09$

## Brute Force Approach

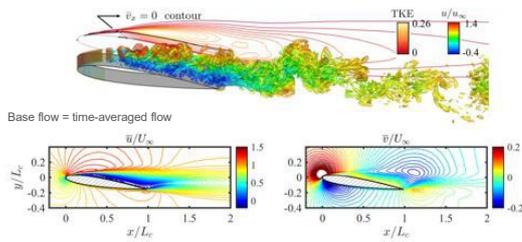
If you can afford lots of computations...

- Computational expense: > 35 million cpu hours...
- Want to avoid expensive parametric LES studies



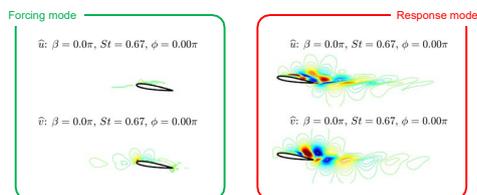
## Base Flow

- Spanwise periodic turbulent flow over a NACA0012 airfoil at  $Re = 23,000$ ,  $\alpha = 9^\circ$ .
- Resolvent analysis about time/spanwise-averaged flow.



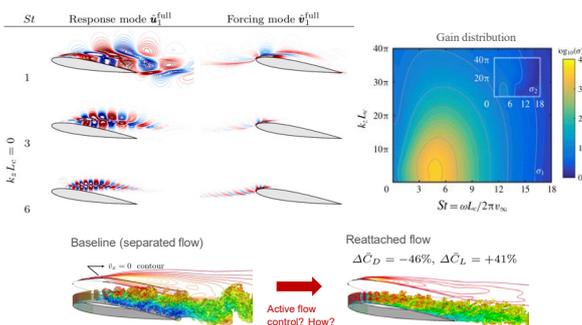
## Resolvent analysis

- Resolvent analysis uncovers the dynamic relationship of how forcing/perturbations can be amplified by the linearized Navier-Stokes operator over the base flow (time-averaged flow)



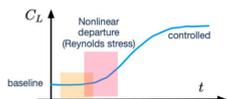
- The leading forcing mode represents the most amplified input/spatial structures
- Response mode reveals the regions where unsteady fluctuations appear

## Resolvent Analysis



## Departure from Linear Analysis

- Mean flow is modified by nonlinear dynamics via Reynolds stress!
- Evaluate the streamwise, transverse, and spanwise resolvent Reynolds stress using the dominant response mode.



$$\hat{R}_x(k_x, \omega) = \text{Re}(\hat{\psi}_x^* \hat{\psi}_x)$$

$$\hat{R}_y(k_y, \omega) = \text{Re}(\hat{\psi}_y^* \hat{\psi}_y), \quad \hat{R}_z(k_z, \omega) = \text{Re}(\hat{\psi}_z^* \hat{\psi}_z)$$

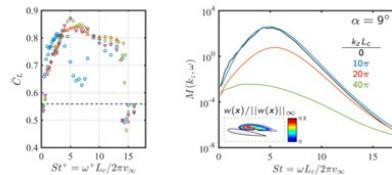
$k_x^+ L_c$	$St^+$	$\Delta \bar{C}_L$	$\Delta \bar{C}_D$	$\hat{R}_x(k_x L_c, St)$	$\hat{R}_y(k_y L_c, St)$	$\hat{R}_z(k_z L_c, St)$
0	1	+34%	-10%			
10π	4	+45%	-33%			

## Metric for Separation Suppression

- We quantify the aerodynamically favorable mixing by spatially integrating resolvent Reynolds stress over a shear-layer window

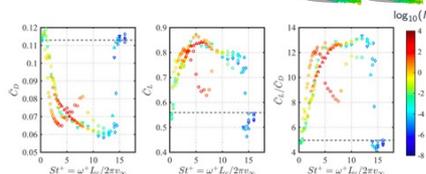
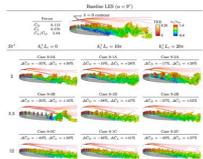
$$M(k_x, \omega) \equiv \int_{\Omega} \left[ \sigma^2 (\hat{R}_x^2 + \hat{R}_y^2 + \hat{R}_z^2) \right]_{k_x, \omega} w(x) dx$$

- In some sense, this is our version of "Bode" type guideline...



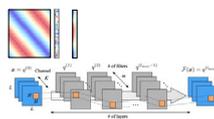
## Flow Control Validation with LES

- The resolvent-based mixing metric correlates well with enhanced aerodynamics performance
  - drag reduction, lift enhancement, lift-to-drag ratio
- Agrees with extensive parametric LES study (35 million hrs)
- Resolvent analysis can be used as a guiding tool for separation control



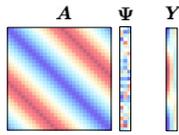
## Expanding the Horizon with Data Science

RANDOMNESS, SPARSENESS, & MACHINE LEARNING



## Randomized Numerical Linear Algebra

- When we only aim to extract information on the **dominant modes** why should we handle the full resolvent operator?
- Instead of handling the full matrix, we can use **randomized techniques\*** to seek the **low-rank approximation** to save on **computation and memory**.

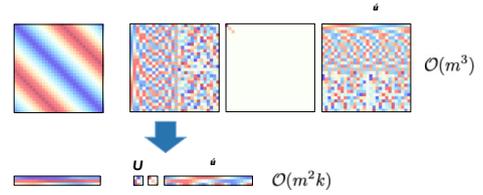


Use **sketching** to extract important information from large  $A \in \mathbb{C}^{m \times m}$

- Test matrix (randomly generated)  $\Psi = \text{rand}(m, k) \in \mathbb{C}^{m \times k}$
- Sketch  $Y \in \mathbb{C}^{m \times k}$

## Randomized SVD

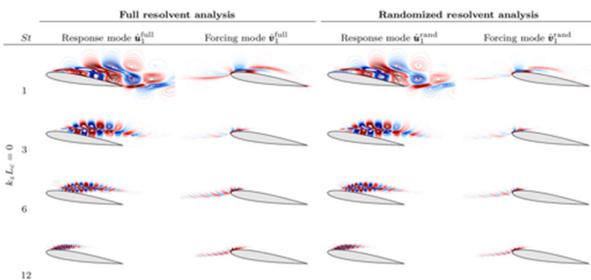
Randomized SVD deals with the low-rank approximation of full operator  $A$



- Also achieves memory savings
- Almost always satisfies theoretical error bound (due to use of random test matrix)
- Applied to randomized POD<sup>1</sup>, randomized DMD<sup>2</sup>, randomized resolvent analysis<sup>3</sup>, randomized fluid flow network characterization<sup>4</sup>

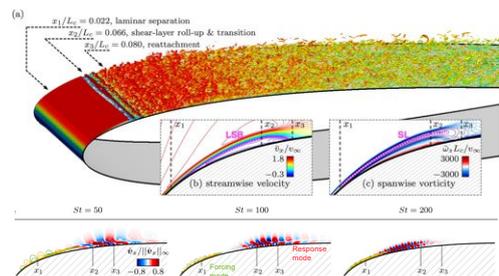
## Randomized Resolvent Analysis

Let us use randomized resolvent analysis with a text matrix of width  $k = 10$ .



## Applications to Higher Re Flows

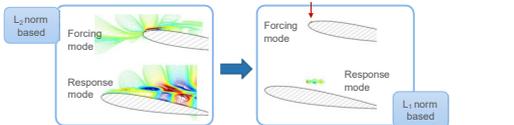
- Mean flow over NACA 0012 at  $Re = 500,000$  (courtesy: Stuart Benton/AFRL)
- Resolvent operator:** 0.9-million  $\times$  0.9-million; Number of sketches ( $k = 5$ )



## Sparse Compression

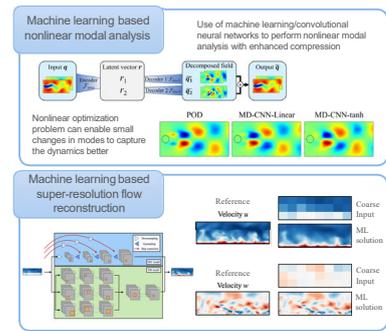
We can use sparse promoting techniques for

- Deriving physically correct and interpretable models
  - Example: Sparse nonlinear models (e.g., SINDy)
- Revealing important physical features
  - Example: Sparse resolvent analysis (identifies optimal actuator and sensor locations)



## Machine Learning

- Extract features and patterns through numerous mathematical techniques
- Regression (model fitting), pattern recognition, classification, etc.
- These problems can be formulated as **nonlinear optimization problems**
- Physical insights can make the machine-learning process easier and robust.



## Concluding Remarks

PROGRESS AND OUTLOOK

## My Evolving Perspective

- Modal analysis, data science (DS), and machine learning (ML) are offering refreshing approaches to tackle some data intensive problems. Recent developments are very exciting and novel!
  - Deep learning (universal approximator), sparse modeling (alternative norms), randomized techniques (low-rank approximation)
  - Many of these techniques were not possible a decade ago.
- Modal analysis and DS/ML are NOT the silver bullets to solve hard problems in fluid mechanics. These powerful tools can certainly help a lot.
  - Must not "oversell" these techniques.
  - We must understand the limitations and further develops techniques to remove such hurdles.
  - Example (FFT): We take FFT as a great tool. Do not expect FFT to "solve" problems. It is up to how effectively they can be "used" to extract insights.

## My Evolving Perspective

- Data structure, quality, and size from fluid mechanics are quite different from what are used in the general DS/ML communities.
  - Our data is huge. May not be easily compressed for broadband flows.
- The quality and reliability of the results from modal analysis and DS/ML are only as good as what are provided to the algorithms. Input data need to be of high fidelity and quality.
  - Remember... garbage-in-garbage-out; contrapositive is not always true...
  - Need to have seen what you want to learn! e.g., kids!!!
- CFD and experiments must be performed flawlessly. We still need talented experts in fluid dynamics to produce good data with careful verification and validation.
  - High-quality CFD and experiments are ever more important.
- Data-driven techniques will continue to become important and powerful. There is no choice but to make sure we fluid mechanics keep up with the surge of new and powerful approaches!

## Summary

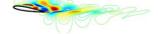
- We presented an overview of modal analysis techniques for fluid flow problems.
- Helpful for flow analysis, modeling, control and design processes.
- Exciting new methods from data science and machine learning are further empowering model analysis techniques.
- Reliance on systematic/mathematical methods to analyze flow data is going to become ever more important as we will be overwhelmed with DATA.

### Acknowledgements

- Students, postdocs, colleagues, and sponsors
- Prof. Kajishima, Prof. Fukagata
- AdvanceSoft (Mr. Yoshidome, Mr. Ohnishi, Mr. Itahashi)



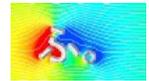
$\bar{u}: \beta = 0.0\pi, St = 0.67, \phi = 0.00\pi$



$\bar{v}: \beta = 0.0\pi, St = 0.67, \phi = 0.00\pi$



We welcome your feedback and questions.  
Please email Kunihiko Taira (ktaira@seas.ucla.edu).



# 畳み込みニューラルネットワークの 流体解析への応用

## (講演概要と参考資料へのリンク)

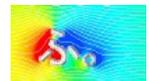
慶應義塾大学 理工学部 機械工学科

深潟 康二

研究室HP: <http://kflab.jp>

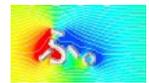
E-mail: [fukagata@mech.keio.ac.jp](mailto:fukagata@mech.keio.ac.jp)

## 講演の概要



2/4

- 「機械学習による乱流ビッグデータ特徴抽出手法の構築」に向けて
  - 広範なスケールを含んだ流れの時系列変化を、機械学習できるか？
    - チャンネル乱流の断面流速分布の**時間発展の学習** (CNN + MLP)  
(Fukami, Nabae, Kawai, and Fukagata, *Phys. Rev. Fluids* 4, 064603, 2019)
    - 2次元減衰乱流の**Super-resolution**解析 (DSC/MS-CNN)  
(Fukami, Fukagata, and Taira, *J. Fluid Mech.* 870, 106-120, 2019)
      - ⑦ **十分な精度で学習・再生成できた！**
  - 機械学習を用いて抽出された低次元モードに対する支配方程式の導出
    - 2次元・低Re数の物体周り流れで試行
      - **異なるRe数, 物体形状での予測** (CNN + LSTM)  
(Hasegawa, Murata, Fukami, and Fukagata, *Theor. Comput. Fluid Dyn.* 34, 2020;  
Hasegawa, Murata, Fukami, and Fukagata, *Fluid Dyn. Res.*, 2020 to appear)
      - CNNで得られる**非線形低次元モードの可視化** (MD-CNN)  
(Murata, Fukami, and Fukagata, *J. Fluid Mech.* 882, 2020)
      - **非線形低次元モードの支配方程式の導出** (CNN + SINDy)  
(Fukami, Murata, and Fukagata, arXiv:2010.12177 [physics.flu-dyn], 2020)
        - ⑦ **ある程度うまくいきそう**

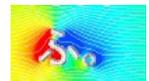


## ● 基礎

- 空間方向に加え、時間方向の超解像  
(Fukami, Fukagata, and Taira, *J. Fluid Mech.* (2021 to appear))
- CNN-AEの3次元場への適用  
(Nakamura, Fukami, Hasegawa, Nabae, and Fukagata, arXiv:2010.1335 (2020))
- より容易な解釈・高い圧縮を可能とするネットワーク構造  
(Fukami, Nakamura, and Fukagata, *Phys. Fluids* **32**, 2020)
- 不確かさの評価 (UQ)  
(Maulik, Fukami, Ramachandra, Fukagata, and Taira, *Phys. Rev. Fluids* **5** (2020))

## ● 応用

- 実験 (PIV) データの補完  
(森本, 卒論2020; Morimoto, Fukami, and Fukagata, *Phys. Rev. Fluids* (in review))
- 流れの制御則構築への応用  
(兼平, 卒論2021 (予定))
- LES壁モデル構築への応用  
(Moriya et al., APS-DFD 2020; 守矢, 卒論2021 (予定))



## ● 本日の内容のダイジェスト版+乱流制御のスライド

第3回CAEワークショップ ~スーパーコンピュータ「京」から「富岳」へ CAEシミュレーションの最前線~

[https://www.hpci-office.jp/invite2/documents2/ws\\_cae\\_191205\\_fukagata.pdf](https://www.hpci-office.jp/invite2/documents2/ws_cae_191205_fukagata.pdf)

## ● 上記スライド以降の成果

深淵研究室・「基盤Aのページ」

<https://kflab.jp/ja/index.php?18H03758>



<http://kflab.jp>  
「基盤Aのページ」  
サンプルPython  
コードもあります

# 価格および弊社サービスのご紹介

営業部 吉留 隆也

オンラインセミナー「機会学習と流体シミュレーション」  
2020年11月13日（金）  
アドバンスソフト株式会社

## アドバンスソフトが提供するソフトウェア

種類	ソフトウェア名
第一原理計算ソフトウェア	Advance/PHASE
ナノ材料解析統合GUI	Advance/NanoLabo
ニューラルネットワーク分子動力学システム	Advance/NeuralMD
流体解析ソフトウェア	Advance/FrontFlow/red
気液二相流解析ソフトウェア	Advance/FrontFlow/MP
構造解析ソフトウェア	Advance/FrontSTR
音響解析ソフトウェア	Advance/FrontNoise
圧縮性流体解析ソフトウェア	Advance/FOCUS-I
3次元TCADシステム	Advance/TCAD
管路系流体解析ソフトウェア	Advance/FrontNETシリーズ
汎用プリポストプロセッサ	Advance/REVOCAP
大規模電磁場解析ソフトウェア	Advance/Parallel Wave

※赤文字で記載されているソフトウェアは国プロで開発されたソフトウェアです。

# アドバンスソフトのソフトウェアの特徴

1. 国プロから現在までソフトウェアを**自社開発**
2. お客様の課題に即した、**カスタマイズ**や**機能追加**が可能
3. 開発チームによる**手厚いサポート**
4. 大規模・並列計算を低コストで実現。  
**並列数無制限**、追加料金なし。

## スーパーコンピューティング・サービス ①

### 搭載実績一覧

- ・富岳  
\*理化学研究所計算科学研究機構様
- ・京  
\*理化学研究所計算科学研究機構様
- ・FOCUSスパコン  
\*計算科学振興財団様
- ・地球シミュレータ(大規模共有メモリシステムUV2000)  
\*海洋研究開発機構様
- ・各大学様のスーパーコンピューター

## スーパーコンピューティング・サービス ②

- 産業利用コンサルティングサービス
  - ・スーパーコンピュータでのソフトウェア使用説明
  - ・シミュレーション全般のコンサルティング
  - ・スーパーコンピュータの利用申請支援  
(ソフトウェアに関する部分の申請書作成支援等)
  - ・解析作業代行

価格はお見積りいたします。  
お気軽にお問い合わせください。

## アドバンスソフトの開発・解析サービス

お客さまのご要望に応じて科学技術計算ソフトウェアの  
新規開発、機能追加、受託解析等のサービスをおこないます。



1. 流体・構造・ナノ関連など幅広い分野のソフトウェアを開発し、解析経験がある技術者がお客様のご要望をお伺いいたします。

2. 最適な解析方法をご提案いたします。

3. お客様のご了解が得られましたら、モデリングを行い、解析を実施いたします。

4. 解析結果を可視化し、解析結果の評価や考察を行なって報告書を作成いたします。



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