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研究課題名（和文）Computational research of biomimetic flight in unsteady environments with the aid of machine learning

研究課題名（英文）Computational research of biomimetic flight in unsteady environments with the aid of machine learning

研究代表者
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研究成果の概要（和文）：この研究は、羽ばたき飛行のデータ駆動型モデリングと組み合わせた高性能コンピューティングを注目した。 飛行測定に基づいた翼ヒンジのばね - 質量 - ダンパーモデル、翼変形の質量 - ばねモデル、前縁渦の低次元化モデル、制御器設計用と平衡の探索用データ駆動型空気力学モデルが開発された。極小甲虫の翼の空力特性が研究された。

研究成果の学術的意義や社会的意義
Quantitative analyses of the aerodynamic and aeroelastic mechanisms of flapping flight have improved our understanding of the morphological diversity of insects. The knowledge and tools developed in this project will serve to construct insect-inspired micro aerial vehicles.

研究成果の概要（英文）：This project focused on high-performance computing in combination with data-driven modelling to explore flapping flight. From the standpoint of fluid-structure interaction of flexible elements, a low-order spring-damper model of the wing hinge has been constructed upon micro-CT and in-flight measurements (Kolomenskiy et al. 2019, J Fluids Struct 91:102628) and a mass-spring model of wing deformation has been developed (Truong et al. 2020, Comput Fluids 200: 104426) and fitted with static bending data (Truong et al. 2021, Bioinspir Biomim, under review). A reduced-order model has been proposed (Chen et al 2018, Phys Rev Fluids 3:114703) to explain the leading-edge vortices. A data-driven aerodynamic model has been developed for controller design and trimmed state search (Cai et al 2021, J Fluid Mech 915:A114). The aerodynamics of tiny bristled wings has been addressed (Farisenkov et al 2020, Exp Fluids 61:194).

研究分野：Fluid dynamics and biomechanics of animal flight

キーワード：insect flight　bio-inspired flight　HPC

１．研究開始当初の背景
Background of the start of research

Accurate account for complex unsteady environment of a flapping flier requires numerical solution of the Navier-Stokes equations. Much of the recent animal flight research focused on unsteady regimes. In particular, there has been a growing number of experimental studies on flight in unsteady wind (Liu et al, Acta Mech Sin 33, 2017; Liu et al, Phil Trans R Soc B 371, 2016). From the perspective of numerical simulation, it has become common to model unsteady maneuvers using prescribed kinematics from experiments (Bomphrey et al, Nature 544, 2017), but fully coupled fluid-structure interaction (FSI) simulation of controlled free flight remains a challenge. Computational studies of flapping flight control are being carried out at Chiba University (Noda et al, J Biomech Sci Engrg 9, 2014) and Kyoto University (Nakatani et al, Comput Fluids 133, 2016), in particular. Decision making for control is gaining attention (Portelli et al, Sci Rep 7, 2017). The potential of machine learning in such context has been demonstrated in a recent study on thermal soaring (Reddy et al, Proc Natl Acad Sci 113, 2016).

２．研究の目的
Purpose of research

The purpose of the proposed research project was to gain physical understanding of biological flight dynamics in unsteady environment by means of development of mathematical models that would account for specific biomechanical aspects of the flapping flight apparatus, its sensory and control system, and the surrounding unsteady aerial environment. The models are based upon direct numerical simulation of the aerodynamic problem, high-fidelity morphological measurements of bumblebees acquired in laboratory, and machine learning techniques for control decision.

３．研究の方法
Methods of research

The research implemented in this project relied upon morphometric and kinematic data acquired in external collaborations (Prof. Hao Liu lab at Chiba University, Prof. Fritz-Olaf Lehmann lab at Rostock University, Prof. Alexey Polilov lab at Lomonosov Moscow State University) and subsequent numerical modelling using high-performance computing. One of the challenges of the insect flight modelling, in particular in unsteady environment, is to accurately resolve the multitude of temporal and spatial scales considering the insect as a complex, time-dependent geometry. To this end, in collaboration with colleagues from TU Berlin, ENS Paris and Aix-Marseille University, we previously developed a Navier-Stokes solver based on a pseudo-spectral method with volume penalization (Engels et al. 2016, SIAM J Sci Comput 38:S3-S24). The penalized Navier-Stokes equations were solved on an equidistant uniform Cartesian grid using a Fourier pseudo-spectral discretization. This method was used until the final year of this project, in particular, for the bumblebee wing pitching rotation simulations.

However, the micro-insect simulations during the final year of the project revealed that the equidistant Cartesian discretization sets a severe limitation on the minimum size of the geometrical features, and in practice does not allow to model the thin bristles that protrude from the wings and generate a considerable aerodynamic force. For that purpose, an adaptive Navier-Stokes solver has been introduced in the project (Engels et al. 2021, Commun Comput Phys, in press). The solver implements dynamic mesh adaptation based on error control using wavelets. For solving the optimization problems in the machine learning tasks, the covariance matrix adaptation-evolution strategy (CMA-ES, Hansen et al. 2003, Evol Comput 11(1):1-18) has been employed.

４．研究成果
Research results

High-performance computing in combination with data-driven modelling has been employed to explore four different aspect of flapping flight of animals. The **first** one is the fluid-structure interaction of flexible structural elements. It has been shown that the wings of bumblebees during flapping undergo pitching rotation that can be characterized as a fluid-structure interaction problem. Measurements of shape, size and inertial properties of the wings of bumblebees *Bombus ignitus* provided the necessary input data for numerical modelling (Kolomenskiy et al. 2019, J Aero Aqua Bio-mech 8(1):41-43). Thus, a spring-damper model of the wing hinge has been constructed. It was combined with a computational fluid dynamics solver. The modelproduced realistic wing motion, see Fig. 1, and accurate time-average estimates of the aerodynamic performance in hover, revealing that the hinge stiffness is slightly offset away from the maximum aerodynamic efficiency (Kolomenskiy et al. 2019, J Fluids Struct 91:102628). Further, mass-spring model of wing deformation has been developed (Truong et al. 2020, Comput Fluids 200:104426) and integrated into a fluid-structure interaction solver based on a pseudo-spectral code for solving the incompressible Navier-Stokes equations. The no-slip boundary condition was imposed through the volume penalization method; the time-dependent complex geometry was then completely described by a mask function. This allowed solving the governing equations of the fluid on a regular Cartesian grid. The mass-spring model uses a functional approach, thus modeling the different mechanical behaviors of the veins and the membranes of the wing. A series of numerical validation simulations has been performed including simulation of a flexible revolving bumblebee wing. Then, the model was fitted with laboratory measurement data of a blowfly *Calliphora vomitoria* (Truong et al. 2021, Bioinspir Biomim, under review). The model was trained to reproduce the static elasticity measurements by optimizing its parameters using a genetic algorithm with covariance matrix adaptation (CMA-ES). Trained wing models were then coupled to the fluid-structure interaction solver, revealing low intra-species variability of elastic properties.

(a) (b)

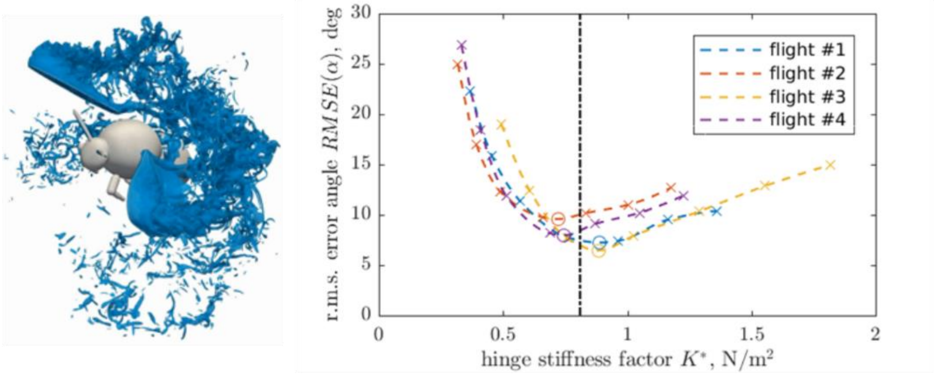

Fig. 1: (a) Q-criterion visualization of the flow past a flying bumblebee. (b) Parameter search for the best-fit hinge stiffness.

The **second** aspect is the aerodynamics and flight control. A reduced-order model has been proposed (Chen et al 2018, Phys Rev Fluids 3:114703) to explain the leading-edge vortices, which is an aerodynamic mechanism of major importance for animal flight. Further, a data-driven aerodynamic model has been developed for controller design and trimmed state search (Cai et al 2021, J Fluid Mech 915:A114). The data-driven aerodynamic model was informed by computational fluid dynamics (CFD) simulations using overset meshes to enable the precise and fast prediction of both cycle-averaged and transient aerodynamic force (Fig. 2), torque and power with various flying motions and wing kinematics. The least square method and surrogate modelling were employed to achieve aerodynamic coefficient fitting through training using a CFD database. A genetic optimization algorithm embedded with CDAM has been employed to determine trimmed states in forward flight. A proportional-derivative-based longitudinal flight controller has been implemented, with the control parameters optimized by Laplace transformation and the root locus method. The results demonstrated that CDAM provided a versatile tool to achieve fast and precise aerodynamical prediction for the flapping flight in various flight behaviours.

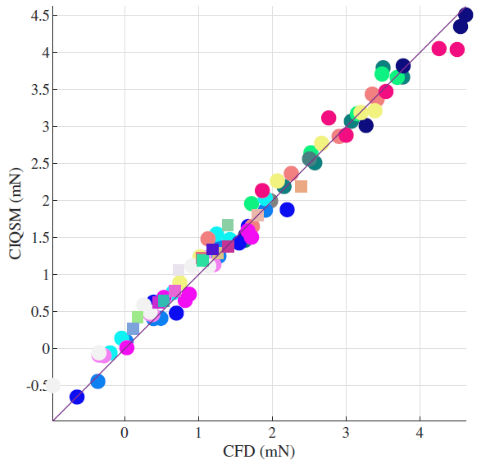

Fig. 2: Comparison between the vertical aerodynamic force prediction using the computational fluid dynamics model (CFD) and the CFD-informed data-driven aerodynamic model (CDAM).

Aerial perturbations are ubiquitous in the outdoor environment. This motivated the **third** aspect of the study. Flapping flight in a highly turbulent environment has been analyzed using the bumblebee model, tethered and in free flight (Engels et al 2019, Phys Rev Fluids 4:013103). The latter allowed six degrees of freedom of the body, coupled with the Navier-Stokes equations. The turbulence intensity and the spectral distribution of turbulent kinetic energy have been varied. Modifying the turbulence intensity showed no significant impact on the cycle-averaged aerodynamical properties, compared to laminar inflow conditions. The fluctuations of aerodynamic observables, however, significantly grew with increasing turbulence intensity but significantly reduced when the integral scale was smaller than the wing length.

The **fourth** aspect concerned with the flight of micro-insects with the body length less than 1 mm. Aerodynamic force generation capacity of the wing of a miniature beetle *Paratuposa placentis* was evaluated using a combined experimental and numerical approach. The wing had a peculiar shape reminiscent of a bird feather, often found in the smallest insects. Aerodynamic force coefficients were determined from a dynamically scaled force measurement experiment with rotating bristled and membrane wing models in a glycerin tank. Subsequently, they were used as numerical validation data for computational fluid dynamics simulations using an adaptive Navier-Stokes solver. The latter provided access to important flow properties such as leakiness and permeability. It was found that, in the considered biologically relevant regimes, the bristled wing functioned as a less than 50% leaky paddle, and it produced between 66 and 96% of the aerodynamic drag force of an equivalent membrane wing. The discrepancy increased with increasing Reynolds number. It was shown that about half of the aerodynamic normal force exerted on a bristled wing was due to viscous shear stress (Farisenkov et al 2020, Exp Fluids 61:194). Further, the numerical simulation has been extended to the flapping kinematics of *P. placentis*, see Fig. 3.

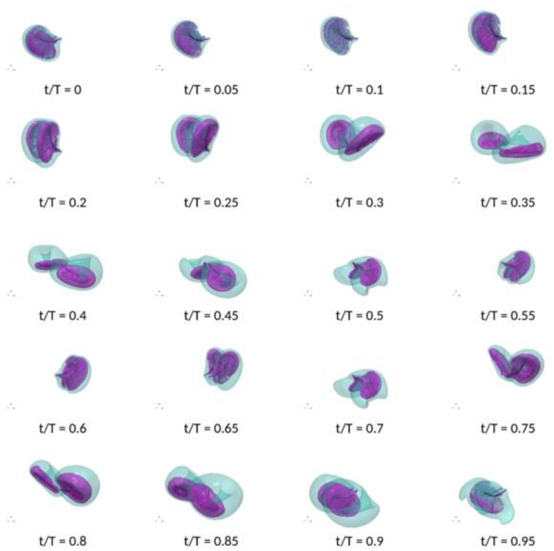

Fig. 3: Flapping bristled wings of a very small insect. Iso-surfaces at two different levels of the vorticity magnitude plotted with the time interval $\Delta t/T=0.05$.

5．主な発表論文等

〔雑誌論文〕　計9件（うち査読付論文　9件／うち国際共著　8件／うちオープンアクセス　6件）

1．著者名 Truong Hung、Engels Thomas、Kolomenskiy Dmitry、Schneider Kai	4．巻 200
2．論文標題 A mass-spring fluid-structure interaction solver: Application to flexible revolving wings	5．発行年 2020年
3．雑誌名 Computers & Fluids	6．最初と最後の頁 104426～104426
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.compfluid.2020.104426	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Kolomenskiy Dmitry、Ravi Sridhar、Xu Ru、Ueyama Kohei、Jakobi Timothy、Engels Thomas、Nakata Toshiyuki、Sesterhenn Joern、Schneider Kai、Onishi Ryo、Liu Hao	4．巻 91
2．論文標題 The dynamics of passive feathering rotation in hovering flight of bumblebees	5．発行年 2019年
3．雑誌名 Journal of Fluids and Structures	6．最初と最後の頁 102628～102628
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.jfluidstructs.2019.03.021	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Kolomenskiy Dmitry、Ravi Sridhar、Xu Ru、Ueyama Kohei、Jakobi Timothy、Engels Thomas、Nakata Toshiyuki、Sesterhenn Joern、Farge Marie、Schneider Kai、Onishi Ryo、Liu Hao	4．巻 8
2．論文標題 Wing Morphology and Inertial Properties of Bumblebees	5．発行年 2019年
3．雑誌名 Journal of Aero Aqua Bio-mechanisms	6．最初と最後の頁 41～47
掲載論文のDOI（デジタルオブジェクト識別子） 10.5226/jabmech.8.41	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

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掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevFluids.4.013103	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Chen Di、Kolomenskiy Dmitry、Onishi Ryo、Liu Hao	４．巻 3
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevFluids.3.114703	査読の有無 有
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２．論文標題 Bees with attitude: the effects of directed gusts on flight trajectories	５．発行年 2018年
３．雑誌名 Biology Open	６．最初と最後の頁 bio034074
掲載論文のDOI（デジタルオブジェクト識別子） 10.1242/bio.034074	査読の有無 有
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１．著者名 Kolomenskiy Dmitry、Farisenkov Sergey、Engels Thomas、Lapina Nadezhda、Petrov Pyotr、Lehmann Fritz-Olaf、Onishi Ryo、Liu Hao、Polilov Alexey	４．巻 61
２．論文標題 Aerodynamic performance of a bristled wing of a very small insect	５．発行年 2020年
３．雑誌名 Experiments in Fluids	６．最初と最後の頁 194
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s00348-020-03027-0	査読の有無 有
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２．論文標題 A CFD data-driven aerodynamic model for fast and precise prediction of flapping aerodynamics in various flight velocities	５．発行年 2021年
３．雑誌名 Journal of Fluid Mechanics	６．最初と最後の頁 A114
掲載論文のDOI（デジタルオブジェクト識別子） 10.1017/jfm.2021.68	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Truong Hung、Engels Thomas、Kolomenskiy Dmitry、Schneider Kai	4．巻 10
2．論文標題 Influence of wing flexibility on the aerodynamic performance of a tethered flapping bumblebee	5．発行年 2020年
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オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

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４．発表年 2018年

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２．発表標題 The Dynamics of Bumblebee Wing Pitching Motion
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４．発表年 2018年

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４．発表年 2020年

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４．発表年 2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関