Numerical Simulation of Rocket Engine Internal Flows

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In this fiscal year, we have simulated an unsteady cavitating flow with flow rate fluctuation in liquid oxygen pump. Through the unsteady simulations with a long time computation, we could estimate some of the "dynamic gain factors", which are useful to predict whether fluid-induced instability in a rocket turbopump does occur or not, although some further improvements are necessary.

Keywords: rocket turbopump, large eddy simulation, cavitation, dynamic gain factors, shaft vibration

In the past, we have developed a Large Eddy Simulation (LES) code for accurate computations of unsteady flows in turbomachinery, and performed computations of cavitating flows for inducers, which are equipped in the turbopumps in a liquid rocket engine. Particularly, in the case of the inducers, it is known that vortex cavitations from the tip region strongly influence the stability of the turbopumps, and Reynolds Averaged Navie-Stokes (RANS) approaches are invalid to capture the flow fields of such vortex cavitations. Our LES code solves the Navier-Stokes equations of weakly-compressible flow, in which standard or dynamic Smagorinsky model is implemented as sub-grid scale (SGS) model. The code is based on a finite element method with hexahedral elements and has the second-order accuracy both in time and space 1). By the multi-frame of reference function based on an overset method, it is possible to compute rotor-stator interactions 2). For the computation of cavitating flows, we have used the cavitation model proposed by Okita et al. 3) In this model, the evolution of cavitation is represented by source/sink of the vapor phase.

In the last fiscal year, we carried out LES analyses of unsteady cavitating flows where flow rate or pressure at inlet is fluctuated at a certain frequency. The simulation image is shown in Fig. 1. This kind of analyses has a potential to define a so-called "dynamic gain factors" which can be used to make judgements whether unstable cavitation occurs or not. We conducted a feasibility study to estimate the dynamic gain factors in the last fiscal year, and could calculate the factors at a certain condition. However, the last estimations were only performed for the initial transient period after giving the flow rate fluctuation or the pressure fluctuation, and the validity was remained questionable. In this fiscal year, we reestimated some of the dynamic gain factors through long time computations although the recalculation could be only performed for the case of flow rate fluctuation.

In the present simulation, we have employed a test inducer with three helical blades. The total mesh consisted of approximately 8.5 million hexahedral elements. The main calculation conditions were as follows; inlet flow rate was 23 liters/s, rotating speed was 17,700 rpm, and inlet cavitation number was $\sigma = 0.04$. Here, an inlet boundary condition where the inlet flow rate was fluctuated with pressure being constant was imposed to calculate a couple of the dynamic gain factors. Through monitoring the change of pressure and

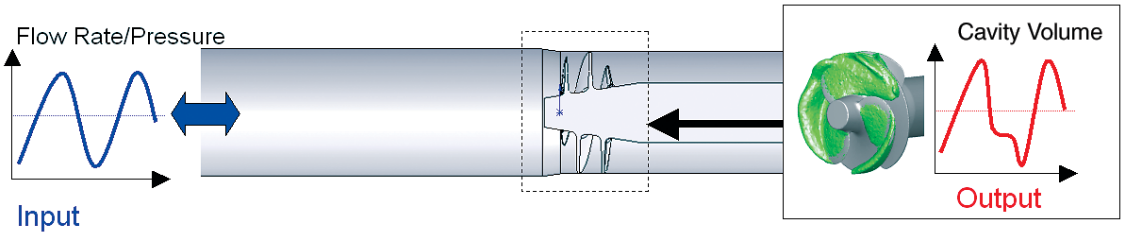


Fig. 1 Schematic of the present method to calculate dynamic gain factors.

that of the cavity volume, we can calculate a head gain (for flow rate change) and mass flow gain factor from this calculation. For reference, some snapshots of the cavitation with flow rate fluctuation are shown in Fig. 2. As is shown in the figure, the vortex cavitation development changes with the fluctuation. The fluctuation frequency of flow rate at inlet was given as one fourth of the rotating frequency of the inducers. In this fiscal year, we conducted a long time computation, and reestimated some of the dynamic gain factors in a time region where a transient behavior just after beginning fluctuation had not been observed. (Note that the fluctuation was started to be given after around 40 revolutions had been performed in order to obtain a fully developed cavitation flow field.)

Figure 3 compares the cavity volume at the initial periods and the periods after 20 revolutions. As is shown in the figure, the amplitude of the fluctuation of the cavity volume gradually increased at the initial periods. In the last fiscal year, we could only estimate the dynamic gain factors in these initial periods. We reestimated the factors for the periods after 20 revolutions where the transient behavior had disappeared, and the calculated factors are shown in Fig. 4. In the present calculation of the two dynamic gain factors, we extracted the mode of the giving fluctuation frequency by an FFT filtering because higher frequncy modes were also included in the change of the head and that of the cavity volume. As is shown in Fig. 4, a constant amplitude was obtained for all cycles, and the amplitude of the head gain

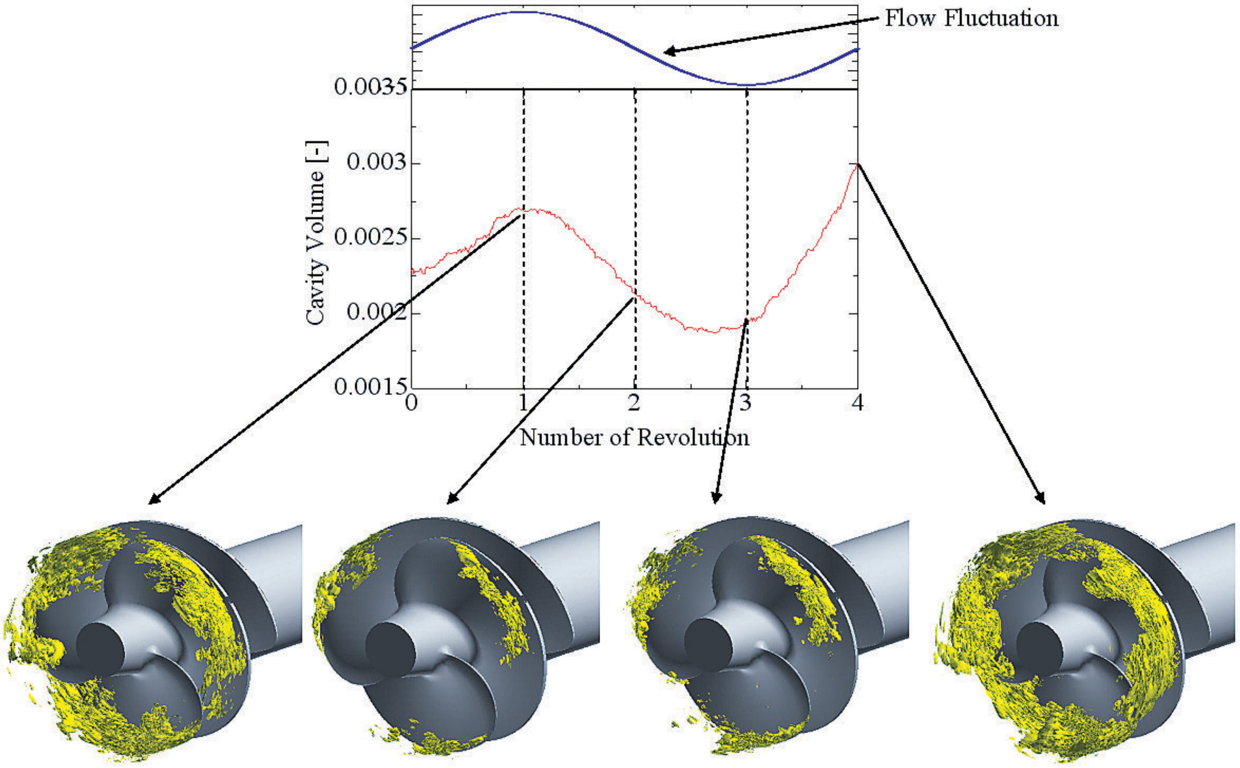
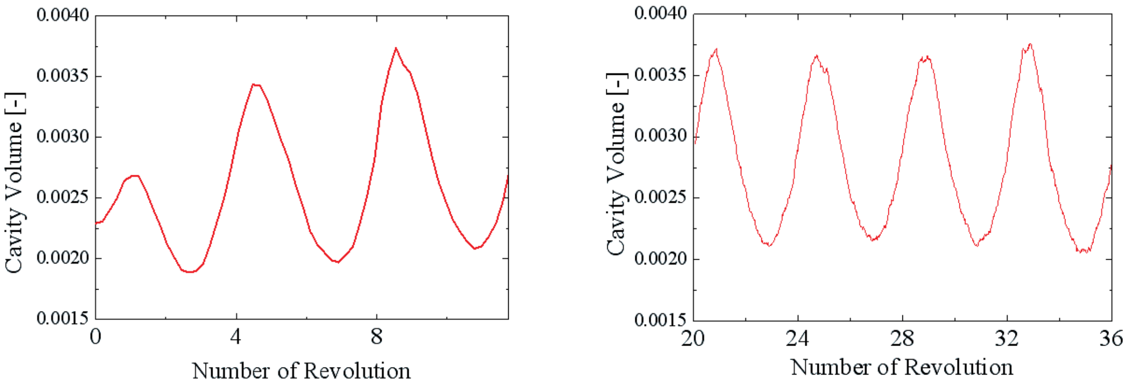


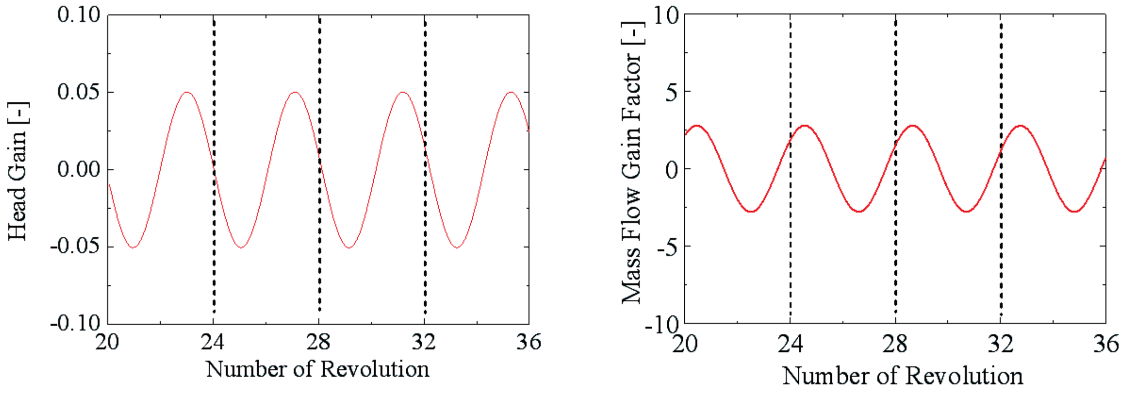
Fig. 2 Some snapshots of cavitation with the non-dimensional cavity volume change.



(a) Initial Transient Periods

(b) Periods after 20 Revolutions

Fig. 3 The time development of the non-dimensional cavity volume.



(a) Head Gain

(b) Mass Flow Gain Factor

Fig. 4 The head gain and the mass flow gain factor obtained in the present simulation.

was estimated to be 0.05 and that of the mass flow gain factor was to be 2.6. In addition, a certain phase delay was also confirmed for each factor. The discussion of the phase difference is sometimes necessary in the case of high frequency fluctuations (quasi-steady approximation is not satisfied), and such kind of information cannot be extracted from steady CFD simulations.

To our knowledge, this was the first calculation result where the dynamic gain factors were derived using a long-time unsteady cavitation CFD with LES analyses. Although a careful validation of the calculated parameters is necessary, it is predicted that our code has a potential to calculate dynamic gain factors directly which is very important to predict whether cavitation instability occurs or not in advance.

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ロケットエンジン内部流れのシミュレーション

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国産ロケットの信頼性向上及び将来型宇宙輸送システムの開発に資するため、主要エンジン要素(燃焼器系・供給器系)で発生している諸問題を再現できるCFDコードを開発し、概念設計・システム評価・不具合対策等に使用し、試作・試験のサイクルを短くすることを目標にプロジェクトを進めている。このうち、本年度はターボポンプの軸振動問題に直結するキャビテーション不安定現象に焦点を絞り、入口部に流量変動を与えた際の揚程やキャビティ体積の応答を調べるための非定常LES解析を実施した。また、キャビテーション不安定の事前予測において重要となる動特性パラメータ(ダイナミックゲインやマスフローゲインファクタ)の算出を試みた。結果として、長時間計算が必要ではあるものの、本手法により各動特性パラメータを数値的に予測し得ることを示した。動特性パラメータは、実験的に求めることが極めて困難であるため、本手法のもたらす波及効果は非常に大きいと考えられる。

キーワード：ターボポンプ, LES, キャビテーション, 動特性パラメータ