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論文内容要旨

Cavitation erosion causes material fracture of the fluid machinery because of the violent collapse of a cavitation bubble or bubble cluster upon arrival at a region where the ambient pressure recovers. The repetition of the bubble collapse causes severe erosion such as material fracture on the material surface when fluid machinery operates for a long time on cavitation. Therefore, the establishment of a method by which to numerically predict the intensity or the amount of cavitation erosion in a cavitating flow is desired from an industrial point of view. However, it is difficult to treat all phenomenon of cavitation erosion from a cavitation collapse to the damage on a fluid machinery after long time operation directly because cavitation erosion is a temporally and spatially multi scale phenomenon and there has not been the practical numerical method yet. Therefore, in the present study, a numerical prediction method of cavitation erosion in a cavitating flow is proposed and the validity of the numerical method is discussed. This prediction method is constituted of following four processes: 1. numerical analysis of a cavitating flow, 2. numerical analysis of the bubble in the flow, 3. evaluation of the impulsive pressure induced by a bubble collapse, 4. evaluation of the intensity of cavitation erosion or quantitative prediction of cavitation erosion from the impulsive pressure.

Cavitation erosion is known to be dependent on a generating cavity pattern. This indicates that accurate numerical simulation of a cavitating flow is important to predict cavitation erosion numerically. In chapter 3, the numerical analysis of the cavitating flow around a hydrofoil is performed using the numerical method based on a compressible locally homogeneous model of a gas-liquid two-phase medium. In the present model, the two-phase medium is treated as a pseudo-single-phase medium, which has a locally homogeneous void fraction. The two-phase flow with cavitation or two-phase medium inside and outside bubble is solved efficiently by this model. Since this model considers the compressibility of the two-phase flow, the propagation of pressure wave can be captured also in liquid phase. The cavitating flows around a Clark Y 11.7% and a NACA0015 hydrofoils are picked up. From the numerical analysis the present numerical method is confirmed to accurately predict the average and the unsteady characteristics of the cavitating flow to some degree. However, the present numerical method is found to largely underestimate the time averaged lift coefficient of a unsteady transient cavitating flow, especially in the flow at high angle of attack. And the influences of the inlet void fraction and the evaporation and condensation coefficients on the numerical analysis of a cavitating flow are investigated. When the inlet void fraction becomes large from small values, the generated pressure becomes small and the high-frequency pressure fluctuation is suppressed firstly and the time averaged characteristics and the cavity behavior change with further increase in inlet void fraction. And the evaporation coefficient is found not to largely influence the flow field around a hydrofoil and the time averaged characteristics of the flow field. On the other hand, the condensation coefficient is found to largely influences the time averaged characteristics and the large condensation coefficient generates the higher pressure when a cloud cavity collapses.

In the present study, the numerical analysis of bubbles in a cavitating flow is performed using the equations of a bubble motion and a bubble oscillation. A one-way coupling algorithm from the analysis of a cavitating flow to the analysis of a bubble is used. In this calculation, the impulsive pressure on a material surface is calculated from the propagating pressure wave induced by a bubble collapse and rebound. In chapter 4, the intensity of cavitation erosion is defined by the impulsive pressure and the intensity of cavitation erosion of the two-dimensional cavitating flow around a Clark Y 11.7% hydrofoil is predicted. In a transient cavitating flow, the predicted intensity of cavitation erosion is high in the vicinity of the sheet cavity termination. On the other hand, the predicted intensities of cavitation erosion in noncavitating, attached cavitating and pseudo-super cavitating flows are far weaker than that at the transient cavitating flow. These results corresponds well to the experimental results and the present numerical prediction method is thought to can capture the systematic erosion characteristics. And the velocity and bubble radius dependence of cavitation erosion are investigated by the numerical prediction method and the intensity of cavitaiton erosion is found to become large when the flow velocity and the bubble radius are large. And it is fount that when the flow velocity becomes large, smaller bubbles have high internal pressures because of the increase in the rate of pressure increase. It is thought that smaller bubbles cause cavitation erosion when the main flow velocity is large.

It has been reported that the pressure wave radiating from a rebounding bubble and the microjet generated from a collapsing bubble near the material surface are the main causes of cavitation erosion. And the bubble behavior and the erosion pattern are dependent largely on the distance between the position of bubble generation and the wall boundary, and the second collapse of the bubble has been reported to generate a high impulsive pressure. Therefore, the clarification of the mechanism of a single nonspherical bubble collapse near a wall boundary is important to understand the fundamental mechanism of the cavitation erosion. In chapter 5, the nonspherical bubble collapse behavior and the induced impulsive pressure are analyzed numerically applying a locally homogeneous model of a gas-liquid two-phase medium to the calculation. From the axisymmetric calculation, it is confirmed that the various phenomena observed in experiment, the micro jet generation and the propagations of the pressure waves induced by the water hammer pressure when the micro jet penetrates to the lower bubble wall and radiated from the rebounding bubble during the first collapse, the counter jet generation during the rebound, and the toroidal bubble collapse attached to the wall boundary during the second collapse, can be realized by the present numerical method. And the second bubble collapses, especially the toroidal bubble collapse attached to the wall boundary, are found to be more violent than the first collapses except for large initial standoff distance. And predicted erosion pattern changes with the initial standoff distance from the wall boundary as follows: Cavitation erosion is expected to be very weak at large initial standoff distance. Center erosion patten is expected when the stand off distance becomes small. Circular and center erosion pattern is expected when the stand off distance becomes small further. In the axisymmetric calculation, high impulsive pressure occurs at every initial standoff distances. However, these results does not agree qualitatively with the experimental results which indicates that strong damage does not occur in the central area at a certain initial standoff distance. The pressure in the central area is thought to be largely influenced by the axisymmetric collapse. Therefore, the collapse behavior of the slightly asymmetric bubble at the initial time is analyzed to investigate the influence of the symmetry breaking of the initial bubble shape on the collapse behavior using three-dimensional plane-symmetric calculation. And the symmetry breaking of initial bubble shape is found to influence largely the bubble second collapse, especially the generation of the high impulsive pressure in the central area. And the ellipsoidal bubble collapse is found to produce the two high pressure points which correspond to the experimental circular erosion pattern which is unevenly distributed at two places. The comparison of the nonspherical bubble collapse near the wall boundary and the spherical bubble collapse far from the wall boundary is performed to get the knowledge to the application of the calculation results of the nonspherical bubble collapse to the numerical prediction of cavitation erosion in a cavitating flow. And it is shown that the impulsive pressure becomes high and the impulsive area becomes small (the high impulsive pressure occurs locally) because of the interaction with the wall boundary when a bubble collapse position from the wall boundary becomes small.

It is confirmed to predict qualitatively the experimental erosion tendency in terms of the position of the cavitation erosion and the erosion characteristics against cavitation number using the present intensity of cavitation erosion. However, the prediction using the intensity of cavitation erosion can not predict cavitation erosion quantitatively. In addition to the prediction of the impulsive pressure due to bubble collapse in a cavitating flow, the relationship between the impulsive pressure and a material response is necessary to be considered to predict the cavitation erosion quantitatively. In chapter 6, the quantitative cavitation erosion models proposed previously are applied to the present numerical results and cavitation erosion is predicted quantitatively. Following three erosion models are used: 1. it is assumed that work hardening occurs without mass loss when a stress acting on a material is between the yield stress and the ultimate tensile strength of the material, and that mass loss starts when the cumulative energy of the material reaches the energy corresponding to the ultimate tensile strength, 2. cavitation erosion is evaluated by a erosion pit produced by the microjet of a collapsing single bubble near the material surface owing to the shock wave associated with a cloud cavity collapse, 3. cavitation erosion is evaluated by the linear relationship between a impact energy and a cavitation erosion. Furthermore, the influence of the nonspherical collapse is considered in chapter 6. The distributions of a erosion rate predicted by the three erosion model have the peak whose positions are close to that of the intensity of the cavitation erosion and the distributions qualitatively correspond to the experimental distributions of the impulsive pressure and the roughness increment on a hydrofoil. The predictions of cavitation erosion of some initial bubble radius are performed and the bubble collapse position is found to be dependent on the initial bubble radius. And when the bubble nuclei distribution is considered, the distribution of a erosion rate is found to be different from the distribution of constant initial bubble radius. And the bubbles with small initial radius are found to become to contribute to the cavitation erosion considering the bubble nuclei distribution because the number of the bubble with small initial radius is relatively large. Comparing the three erosion model, the model which uses the experimental relationship between the impulsive pressure and the cavitation erosion, is found to predict the erosion rate more accurately than the other two models which also simulate the relationship and overestimate the erosion rate.

論文審査結果の要旨

高速液流中に生ずるキャビテーションによる材料壊食は，流体システムの安全性を保証する観点から重要な設計因子とされ，従来から壊食発生の主要因であるキャビテーション気泡崩壊による衝撃圧力の気泡力学的研究や衝撃力と壊食量との相関を用いた耐キャビテーション特性に関する数多くの材料試験が行われてきた。しかしながら、現在、さらなる壊食予測精度の向上を図るため、実際のキャビテーション流れ場での時空間衝撃力頻度分布から壊食量と壊食発生位置を予測できる新たな手法の開発が求められている。本研究では，近年のキャビテーション流れの数値解析技術の発展を背景に，複雑キャビテーション流れ中で生じる壊食の数値予測法を提案し，時空間の壊食量分布を予測する手法を検討している。本論文は，これらの研究成果をまとめたものであり，全編７章からなる。

第１章は序論であり，本研究の背景，目的および構成を述べている。

第２章では，本研究で用いる高速気液二相流動の数値計算手法について述べている。壊食に関わるキャビテーション流れ場と気泡崩壊挙動の数値解析には，液相の圧縮性，気相での凝縮／非凝縮性混合気体を考慮した局所均質媒体モデルと高精度の数値計算手法が検討されており，有益な成果である。

第３章では，二次元翼形まわりのキャビテーション流れの数値計算結果を実験結果とも対比させ議論している。壊食性が顕著となる遷移キャビテーション状態では，翼面上のシートキャビティが破断してクラウドキャビティが放出されるという巨視的な非定常流動場が再現されており，本解析手法の妥当性を示している。これは，重要な成果である。

第４章では，遷移キャビテーション状態を含む翼形まわりの非定常流れ場において，上流から気泡核を流入させ，多数気泡の運動軌跡と体積変動を計算によって求め，さらに気泡力学を用いて評価した壁面衝撃圧力から翼面上の時空間キャビテーション壊食強さを予測している。また，壊食強さは速度のべき乗則となることを見出している。これらの結果は，壊食の数値予測法の開発において重要な成果である。

第５章では，壁面衝撃圧力は気泡が壁面に近付くと気泡中央部を貫通するマイクロジェットを伴う非球状気泡崩壊の影響を受けるため，初期気泡形状が球状および球状に近い回転楕円体状の第一および第二気泡崩壊挙動を数値解析し，壁面までの距離と壁面衝撃圧力との関係を求めている。第一気泡崩壊時の壁面衝撃圧力は気泡直下で発生するが，第二崩壊時では付着型円環状気泡崩壊となるため卓越した壁面衝撃圧力が円形状に発生し，実験観察による壊食痕の様相と符合する結果を見出している。また，それらの距離に依存する高衝撃圧力発生のメカニズムについても検討している。これは，壁面の影響を考慮した壊食強さの評価のために非常に重要な知見である。

第６章では，壁面による非球状気泡崩壊の影響を考慮した壊食強さと既存の４種の壊食モデルを用いて上記の翼形まわりのキャビテーション流れにおける時空間壊食量分布を算出し，定量的な比較検討を行っている。壊食モデルの材料が相違することもあり，壊食量分布はシートキャビティ後端前後で最大となる実験結果に類似しているが，壊食量は定量的にかなり異なり，実験的に求められた衝撃エネルギーに基づく壊食モデルはある程度実験に近い壊食率を予測することを見出している。これは，実用化に向けた重要な成果である。

第７章は結論である。

以上要するに本論文は，「キャビテーション流れ場」，「多数気泡の運動追跡」，「壁面近傍での気泡崩壊衝撃圧力」，「壊食モデルを用いた時空間壊食量分布」の４段階を連結した壊食予測手法を提案し，翼形まわりのキャビテーション流れに対する大規模な数値解析によって本数値予測法の有用性を明らかにしたものであり，機械システムデザイン工学および流体工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。