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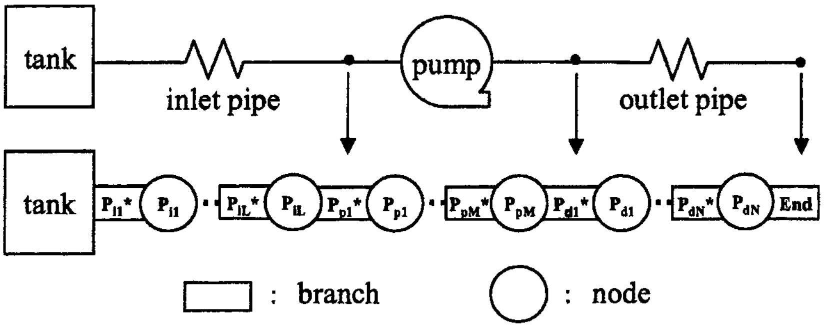
論文内容要旨

With regard to the development of a liquid rocket engine, knowledge of unsteady characteristics of turbopump is essential in attempts to increase the rocket reliability. The turbopump is a key component of liquid rocket engine, which makes high-pressure combustion possible. To realize a high performance rocket, there must be a high-pressure turbopump which is both compact and light, and for realization of these characteristics, such a turbopump must rotate with a very high speed. An inducer is attached to the front of the main impeller to prevent cavitation from occurring there in, since such cavitation results in deterioration of pump suction performance. However, cavitation also arises in the inlet section of the inducer because a very high suction performance is needed for a high-pressure turbopump. Dynamic characteristics of a cavitating turbopump are determined by the system design. They can cause considerable vibration and oscillation problems in a propellant feed system. Therefore, they are known to be the most critical and complex factors on the stability of a rocket engine. The rotating cavitation and the cavitation surge, which are the typical examples of the cavitation-induced instabilities, are main problems in rocket pumps. During a launch sequence, a rocket engine experiences many transient stages such as chilling and engine start, thrust control, engine shutdown and reignition, etc. Stable operations of an engine during these stages are very important design criteria for the rocket engine reliability, and thus unsteady performance tests constitute the major part of rocket engine tests. However, many cost and long time are consumed for the test. Therefore, numerical simulation method is necessary. By conducting the numerical simulation, it is also possible to know the unsteady behavior of a system with a large amplitude oscillation.

In 1960s, many space launch vehicles were developed and launched in USA and Russia. In early attempts, many launches failed because of a system vibration, which was known as the *POGO instability*. POGO is the longitudinal motion of vibration produced by the interaction between the vehicle structure and the propulsion system. To solve this problem, many numerical simulation tools were developed. Sack was the first researcher who had analyzed this instability from the aspect of an auto-oscillation of a hydraulic system. However, the modeling of cavitation was not accurate enough and a quantitatively accurate result was not obtained. Therefore, it was necessary to analyze dynamic characteristics of a cavitating turbopump more quantitatively. At first, only the cavitation compliance was focused on and analyzed. The cavitation compliance (C_B) is defined as the ratio of the cavity volume change rate to the pump inlet pressure change rate. Many researchers had attempted to obtain the experimental data about the cavitation compliance and the numerical simulation result from the cavitating hydrofoil model by Acosta and Stripling was used for comparison. However, there were also some differences. Pratt and Whitney had also analyzed the dynamic characteristics of an inducer and Young et al. had found that the cavitation surge was caused by the increase of the cavity volume related to the decrease in the flow rate. The parameter representing this effect was known to be the mass flow gain factor (M_B), which is defined as the ratio of the cavity volume change rate to the change rate of the pump inlet flow rate. Brennen and Acosta studied the dynamic characteristics of cavitating inducers analytically and tried to express their characteristics by a transfer matrix.

Most analytical models to date for the cavitating flows in rocket engine feed system are based on the incompressible flow. Moreover, many of them are solved by linear methods. However, rocket engine feed system is characterized by compressibility and non-linearity. Therefore, a new analytical model that includes the effect of compressibility and the effect of non-linearity is necessary. In this paper, a new mathematical model of a cavitating compressible flow was developed and the effect of the compressibility of cryogenic propellants, such as liquid hydrogen and liquid oxygen, on the dynamic response of a pumping system was analyzed. Each pumping system of the LE-7 engine, including pipes, was modeled by a one-dimensional non-linear compressible model and the simulation results of dynamic response to the tank pressure drop or pump outlet blowdown pressure drop were compared with those of a non-linear incompressible model. Effects of the cavitation compliance and the mass flow gain factor on system stability were quantitatively analyzed by spectral analyses of the time-dependent simulation results. Moreover, an accumulator, which is used for the POGO suppressor, was modeled and the POGO suppression mechanism was analyzed.

Figure 1 shows the mathematical model for the analysis of a cavitating compressible flow. The pumping system is composed of 3 components, namely, the inlet pipe, the pump, and the outlet pipe. Each component



< Figure 1 > Mathematical model of a compressible flow

is divided into many cells and each cell is composed of a node and a branch. Inlet pipe, pump and outlet pipe are divided into *L*, *M*, and *N* cells, respectively. In the figure, P represents an arbitrary property of fluid, namely, pressure, temperature, and density. Mass flow rate is also defined in each node and branch. The system is modeled so that mass and energy are conserved in each node and momentum is conserved in each branch. Equation of the state is applied in each branch. Cavitation model is applied to the last cell of the inlet pipe.

As the reference values for C_B and M_B of cryogenic propellants, the analytical result by Brennen and Acosta were used. However, these values do not involve the effect of compressibility because those were calculated from water. Therefore, some scale factors were multiplied to these factors and stability analyses were conducted. Simulations were conducted for two cases, one is a case that tank pressure drops suddenly by 5% and the other is a case that pump outlet blowdown pressure drops suddenly by 5%. Inlet boundary is a tank and the outlet boundary is a branch of the last cell of outlet pipe. Pressures of inlet boundary and outlet boundary were used as input variables. Temperature and density of the tank were kept constant and Neumann conditions were applied to the temperature of inlet boundary and the density of outlet boundary, respectively. The time constant of a disturbance was assumed to be 5×10^{-4} second. The resistance coefficient of each cell was determined so that the steady state calculation results were consistent with the experimental data of the LE-7 engine. The inertance coefficient of each cell was calculated taking the system geometry into consideration. Unsteady conditions were calculated using the 4th order Runge-Kutta method until 1 second for a LH_2 pumping system and until 5 seconds for a LOX pumping system.

At first, the effect of dynamic characteristics of turbopump on the dynamic response of a high pressure LH_2 pumping system was analyzed. For the compressible model as well as for the incompressible model, the cavitation compliance (C_B) had a dominant effect on system frequency and the mass flow gain factor (M_B) had a dominant effect on system stability. The effect of C_B in a compressible model was less than that in an incompressible model. The effect of compressibility is summarized as follows. The dynamic response frequency of a compressible model is less than that of an incompressible model and oscillations of the pressure and mass flow rate of a compressible model are more rapidly damped than those of an incompressible model. Particularly, compressibility in the pump absorbs the energy of the disturbances upstream and downstream of the pump and thus the system stability tends to increase.

The effect of the difference of a working fluid was also analyzed. Simulation results of the LOX pumping system were compared with those of the LH_2 pumping system. In the stability analysis maps of the LOX and LH_2 pumping systems, width between the neutral stability lines of the compressible and incompressible models was examined. The width of the LOX pumping system was less than that of the LH_2 pumping system. Difference between the response frequencies of the compressible and incompressible models for the LOX pumping system was also less than that for the LH_2 pumping system. These results show that a LOX pumping system is closer to the incompressible flow than a LH_2 pumping system. For the disturbance downstream of the pump, the damping effect of the compressibility was weak in the LOX pumping system comparing to that in the LH_2 pumping system. As a result, we could know that a disturbance downstream of the pump for the LOX pumping system can have a dominant effect on the cavitation-induced instabilities.

The effect of pipe elasticity was analyzed. It was similar to the effect of cavitation compliance and that effect was large in the LOX pumping system rather than in the LH_2 pumping system. The reason for this seems to be that the LH_2 pumping system has a large compliance due to the large compressibility of LH_2 and has large stability. By attaching an accumulator in the inlet section of the pump, system frequency became low and damping effect became large. Unstable system became stable by attaching the accumulator. The mechanism of POGO suppression by the accumulator could be analyzed by comparing the fluctuation phases of the inlet pressure and the cavity volume. The cavity volume had the same phase with the inlet pressure when the accumulator was not installed. However, it had a different phase from that of the inlet pressure when the accumulator was installed. In this case, the gas volume of the accumulator had almost same phase with that of the inlet pressure. From this result, we could know that an accumulator makes the correlation between the cavity volume and the inlet pressure to be weak and the system stability increases by this effect.

論文審査結果の要旨

液体ロケットの開発においては，ターボポンプの非定常特性に対する予測が、ロケットの信頼性を向上させる上で極めて重要である。従来これらは、数多くの試験によって求めていたが、数値解析によりこれらを予測することができれば開発期間の短縮や開発コストの低減が期待できる．本論文は、極低温推進剤の液体水素と液体酸素の圧縮性や熱力学的特性を考慮して、H-2A ロケット推進剤供給系の動的特性を解析したものであり，全編６章よりなる。

第１章は緒論である。

第２章では，極低温推進剤供給システムの流入配管、ポンプ性能、キャビテーションなどのモデル化について述べている。実機のエンジン試験で得たデータを基にして質量保存、エネルギー保存、運動量保存の各式やポンプ性能および キャビテーションの時間変化などを定式化している。これらの手法により、複雑なエンジンシステムを簡便かつ少数の変数で表現することに成功した。これらは、ロケット推進剤供給系の設計に極めて有用な成果である。

第３章では、液体水素供給システムの動的挙動の解析結果について述べている。外乱として推進剤ポンプ下流側圧力を急激に変化させた系について、液体水素の圧縮性を考慮した計算と考慮しない計算の比較を行って，液体水素の圧縮性が、特にポンプ内部において外乱のエネルギー吸収に大きく寄与し，非圧縮性の計算結果に比べてシステムの安定性が大幅に向上することを明らかにした。この結果は、液体水素系の振動解析をする際には通常の水などの理論をそのまま適用する事ができないことを示唆しており、今後のロケット推進剤供給システムの振動解析に対して重要な指針を与えた。

第４章では、液体酸素供給システムの動的挙動の解析結果について述べている。ポンプに発生するキャビテーション特性に対する液体酸素供給システムの安定・不安定マップを作成し，液体水素供給系との比較を行っている。この結果、液体酸素供給システムの中立安定領域は液体水素供給システムに比べて狭く、より非圧縮流れに近い性質を有していること、ならびに圧力の急激な変化に対するダンピング効果も弱く、より高い周波数の振動が発生することなどを明らかにした。これらの結果は、液体酸素供給システムの設計に対する有用な成果である。

第５章では、液体水素供給システムよりも不安定領域の広い液体酸素供給システムの安定化について解析している。特に、機体と推進剤供給システムが連成して生じるポゴ振動を抑制するアキュムレータの簡便なモデル化に成功して、配管の弾性変形のシステムに与える影響はポンプのキャビテーションコンプライアンスが与える影響と同程度であること、またアキュムレータの装着により、システムの振動周波数が大幅に減少し、ダンピング効果が著しく増大することを明らかにした。これらの知見は、今後のロケットの設計に対して有用な指針を与えた。

第６章は結論である。

以上要するに本論文は、極低温推進剤の LE-7A エンジンのポンプを含む推進剤供給システムに内在する様々な要因の動的挙動に対する影響について述べたものであり、航空宇宙工学ならびに低温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。