Numerical Analysis of Transient Flow Characteristics in Hydraulic Elements(油圧機器内の過渡的流動性に関する数値解析)

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論文内容要旨

Chapter 1. Introduction

The precise understanding of the dynamic flow characteristics in hydraulic control elements is essential for the rational design of hydraulic control systems. The orifice is a fundamental component of a fluid flow system and certain valves can be adequately represented by an orifice. The objective of this thesis is to investigate the transient flow through a pipe orifice and a spool valve via a numerical analysis and make a simplified mathematical model describing the dynamic flow characterristics. The thesis focuses on the variation of time-dependent flow field. The characteristic time constants for the transient state have been studied.

Chapter 2. Numerical Procedure for Incompressible Transient Flow

This Chapter gives the governing equations and numerical procedure for the incompressible transient flow. The discretized representations of the fundamental equations in an equidistant rectangular staggered grid system are obtained through the control volume method. They are solved by an iterative algorithm similar to the SIMPLER method due to Patankar.

The convective terms are discretized by the reformulated QUICK scheme which assures the physical consistency of the numerical solution and greatly improves the numerical stability. For discretizing the time derivative terms, two-time-level implicit scheme is employed.

Chapter 3. Transient Pipe Oriffice Flow Starting from a Stationary State

This chapter performs time-dependent calculation from the initial stationary state under a suddenly imposed pressure gradient. The geometry is described by the axisymmetric cylindrical coordinate system (r, z) with the corresponding velocity components (u, w). A square edged orifice of the thickness b was set at the location z_i along the pipe of the length L. In the calculation a radius of the orifice is fixed to 0.2 and pressure difference between the upstream and downstream boundaries is suddenly changed. The computation was performed on the CRAY Y/MP 8 in the Institute of Fluid Science, Tohoku University.

Variation of the stream lines was plotted using the computational results. At first, the flow field is symmetric about the orifice, showing no separation [Fig. 1 (a)]. As the time passes, the recirculating region appears behind the orifice plate [Fig. 1 (b)], and it grows to reach the steady state [Fig. 1 (c)]. The variations of the flow rate q and the distance of reattachment point z_{ai} normalized with its steady value are plotted in Fig. 2. the present numerical analysis has revealed that the transient pipe orifice flow has shown two distinct characteristic time constants. The settling time of the flow rate mainly agrees well with the characteristic time commonly used in the analysis of the simplified transient flow model, but the complete settling of the flow field is established through the second characteristic time, which is almost ten times larger than the first one for the present condition. The small variation of the flow rate also accompanies the variation of flow pattern. A special attention should be made in the precise measurement of unsteady flow using the orifice meter.

Chapter 4. Transient Pipe Oriffice Flow from an Initial Steady Flow

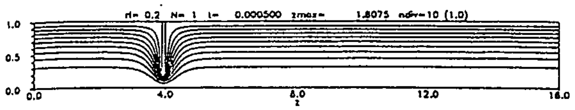
This chapter treats the transient flow starting from an initial steady flow [Fig. 1 (c)] and discusses the effects of the initial recirculating flow and the stretched contraction flow region. Calculation was performed for three cases, where the pressure difference was doubled (Case 1), reduced to zero (Case 2) or changed in the opposite direction (Case 3).Effect of the recirculating flow and stretched contraction flow region on the dynamic behavior is investigated. Numerical results for Cases 1-3 has revealed that the increase (decrease) in flow rate results in increase (decrease) in stream surface atea A_i, while the mean velocity of the contraction w_{im} remains constant. From the computational results, the variation of the streamline near the contraction was obtained in the transient state (Fig. 3). These results confirm the variation of the cross sectional area of the converged flow reduces inertial effect of the converged flow region. In Fig. 4 variation of the flow rate is compared among the numerical result and two simplified mathematical models based on the Bernoulli equation. The model considering the reduced inertial effect shows better agreement with the numerical result than ordinary model.

Chapter 5. Transient Flow Through a Spool Valve

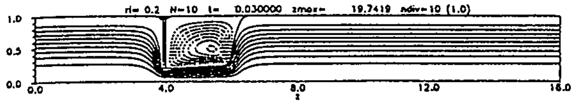
This chapter discusses the transient flow through a spool valve. The dynamic flow characteristics is investigated in relation to the former results on the pipe orifice flow. The steady computation was first made for a variety of pressure difference $\triangle p$. For a pressure difference $\triangle p$ less than a certain value $\triangle p_1^*$, the steady flow solution with a jet angle $\theta = 90°$ is obtained. For a pressure difference $\triangle p$ larger than that critical value, the steady solutions with jet angles $\theta = 90°$ and $\theta = 69°$ are obtained depending on the initial condition. These two distinct flow solutions have a different flow rate q, discharge coefficients c_d. For $\triangle p =$ 160000 ($\triangle p > \triangle p_1^*$), two distinct stream lines are plotted in Figs. 5 (a) and (b). The plot of the steady-state axial flow-force F versus the pressure difference $\triangle p$ is shown in Fig. 6. The flow force for solutions with $\theta = 69°$ and 90° are almost identical. The time-dependent calculations were then made with the initial stationary condition in cases when pressure difference $\triangle p$ is suddenly increased form 0 to 32000 ($\triangle p < \triangle p_1^*$) and 160000 ($\triangle p > \triangle p_1^*$), respectively. The numerical analysis has revealed that variation of the flow pattern is more complicated than the former pipe orifice flow and the time response of flow rate has an overshoot for larger pressure difference $\triangle p$. However the time response of the flow rate is approximated in the same formulation as the pipe orifice flow using an exponential function with two distinct characteristic time constants τ_1 and τ_2.

Chapter 6. Conclusions

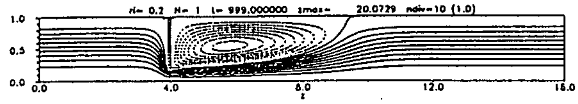
This chapter presents the study conclusions.



(a) t = 0.0005



(b) t = 0.03



(c) steady state

Fig.1 Streamlines for time dependent calculation.

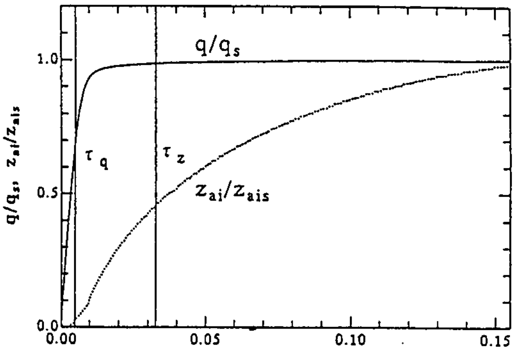
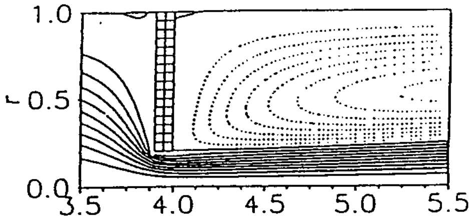
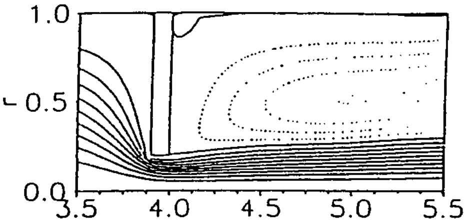


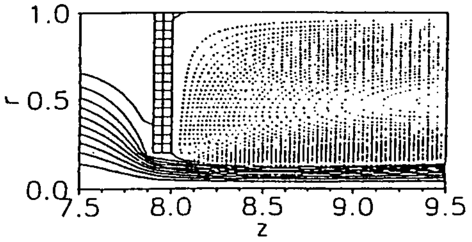
Fig.2 Variation of the flow rate q/q_s and the distance of reattachment point z_{ai}/z_{ais}. (the subscript s represents the steady value, $\triangle p$ = 32000)



(a) Case 0 ($t = \infty$ q = 20.07)



(b) Case 1 (t = 0.002 q = 25.36)



(c) Case 3 (t = 0.002 q = 8.46)

Fig. 3 Comparison of stream lines near the orifice.

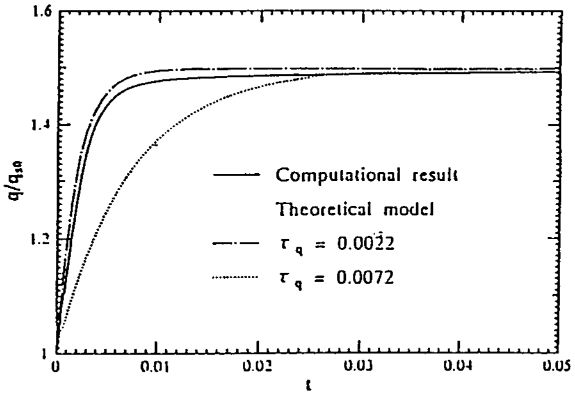


Fig. 4 Variation of flow rate.

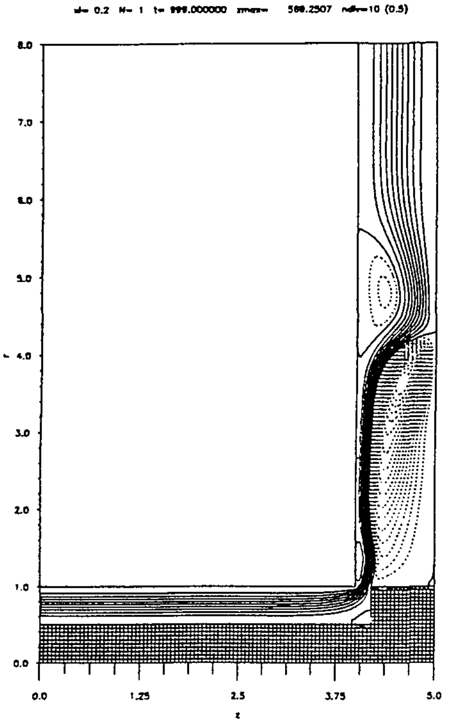


Fig.5(a) Streamline for steady solution. ($\triangle p$ = 160000, θ = 90°)

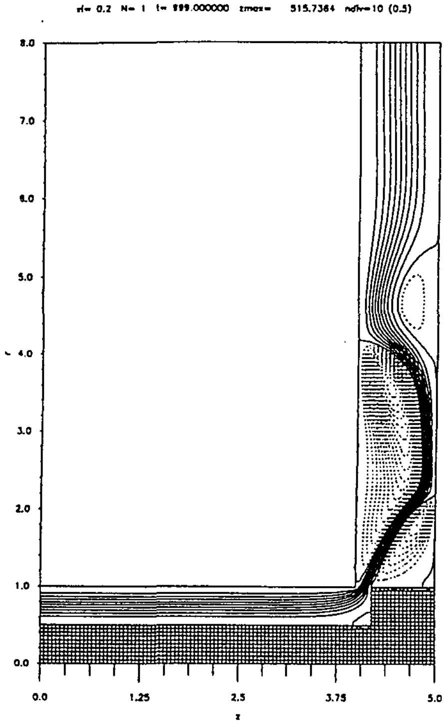


Fig.5(b) Streamline for steady solution. ($\triangle p$ = 160000, θ = 69°)

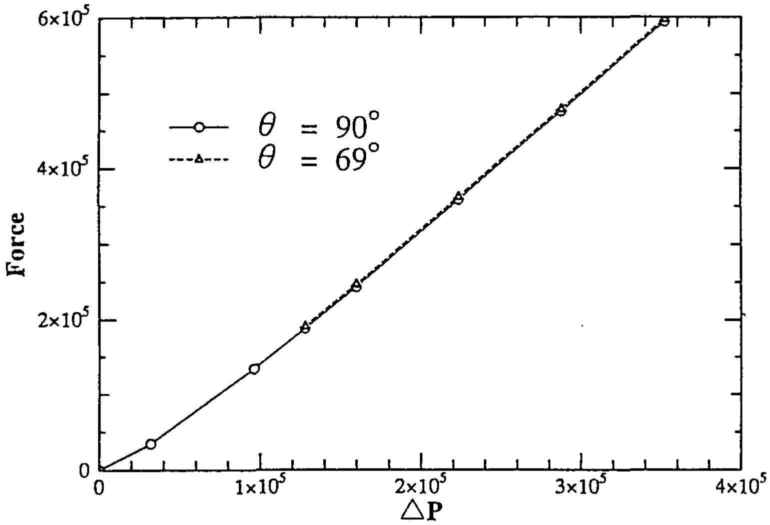


Fig.6 Relation between the steady-state axial flow force F and pressure difference $\triangle p$.

審査結果の要旨

油圧システムの高速化に伴って油圧機器の設計に際して従来より高周波数域での特性に関する知見が必要とされ，従来，静特性としてモデル化されてきた要素の動特性を加味したモデル化が要望されている。

本研究は，油圧機器内の随所に用いられている管オリフィスとスプール弁のメータリング-オリフィスを通過する非定常流を数値解析によって明らかにし，その動特性の簡単な数学モデルを提案し，妥当性を数値解析によって確認したものである。

第1章は序論であり，既往の研究を概観し，研究の背景と目的を述べている。

第2章では，非定常オリフィス流を記述する基礎方程式を導き，これを差分化して数値解析するための計算手法について述べ，さらに，具体的な計算手順について述べている。

第3章では，中間にオリフィスを有する直円管内に静止する流体の上・下流圧をステップ状に変化させた場合の流れの非定常過程を数値解析して，その動的挙動が主として2つの的定数に支配されることを示した。

第4章では，前章で得た定常流動解にステップ状圧力変化を与えて，加速する場合，減速して静止させる場合，減速の後逆流させる場合の3種類の非定常過程を数値解析して，それらの動特性が前章で指摘した2時定数に主として支配されることを示し，さらに，その動特性をオリフィス縮流部の慣性により等価的に表現しうることを示した。

第5章では，スプール弁のメータリング-オリフィスの流れを数値解析して，レイノルズ数の低い領域では同一条件下に2個の定常流動解があること，即ちこの流れには双安定性があることを示し，非定常過程では一方の定常流から他方へスイッチングする現象を明らかにするなど，この種の弁の非定常過程で不明確であった点を明らかにし，動特性の近似モデルを構築するための基礎的知見を得ている。

第6章は結論である。

以上要するに本論文は，油圧機器内の一要素であるオリフィスの非定常過程を数値解析して，その動特性を明らかにしたもので，流体制御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。