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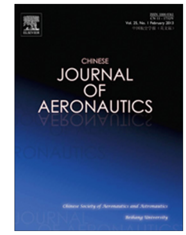

Numerical simulation of a cabin ventilation subsystem in a space station oriented real-time system

Zezheng QIU [a], Liping PANG [a,*], Guoxiang LI [a], Helin ZHANG [b]

[a] *School of Aeronautic Science and Engineering, Beihang University, Beijing 100083, China*
[b] *Aviation Key Laboratory of Science and Technology on Aero Electromechanical System Integration, Nanjing Engineering Institute of Aircraft Systems, Nanjing 211102, China*

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Abstract An environment control and life support system (ECLSS) is an important system in a space station. The ECLSS is a typical complex system, and the real-time simulation technology can help to accelerate its research process by using distributed hardware in a loop simulation system. An implicit fixed time step numerical integration method is recommended for a real-time simulation system with time-varying parameters. However, its computational efficiency is too low to satisfy the real-time data interaction, especially for the complex ECLSS system running on a PC cluster. The instability problem of an explicit method strongly limits its application in the ECLSS real-time simulation although it has a high computational efficiency. This paper proposes an improved numerical simulation method to overcome the instability problem based on the explicit Euler method. A temperature and humidity control subsystem (THCS) is firstly established, and its numerical stability is analyzed by using the eigenvalue estimation theory. Furthermore, an adaptive operator is proposed to avoid the potential instability problem. The stability and accuracy of the proposed method are investigated carefully. Simulation results show that this proposed method can provide a good way for some complex time-variant systems to run their real-time simulation on a PC cluster.

1. Introduction

A space station is a unique laboratory for humans to explore the outer space,[1] and its environment control and life support system (ECLSS) is one of the important systems because it can provide a basic living environment for astronauts. The ECLSS includes some coupled operating subsystems, such as an atmosphere control and supply subsystem (ACSS), a temperature

* Corresponding author.
E-mail address: pangliping@buaa.edu.cn (L. PANG).
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and humidity control subsystem (THCS), a carbon dioxide removal subsystem (CDRS), a trace contaminants control subsystem (TCCS), a water recovery and management subsystem (WRMS), and a vacuum subsystem (VS).[2,3] These coupling subsystems are connected by certain fluid pipe networks which are everywhere in the cabin, such as an air ventilation pipe network and a liquid cooling pipe network.[4] The fluid pipe networks can provide the working pressure and flow rate for components so as to implement flow, heat, and mass transfer or some special chemical reaction processes dynamically. Therefore, correct simulation of pressure-flow coupling performance is the premise of accurate ECLSS dynamic simulation.

Scholars have carried out a lot of research on the dynamic modeling and simulation of ECLSSs. Jones[5] analyzed the relationship between static and dynamic models, and established an environment simulation system including cabin environment, crew metabolic, and waste management models. Boscheri et al.[6] built mechanism models for some processes, such as water treatment and carbon dioxide removal and reduction. Their models can reflect the regenerative performance of an ECLSS. The European Space Agency (ESA) developed EcosimPro software to simulate non-regenerative ECLSSs and an electrolytic oxygen process.[7] Kortenkamp and Bell[8] set up energy supply and food management models to enrich the ECLSS simulation system. Furthermore, a large number of physical-chemical and biological simulation studies about ECLSSs have emerged in recent years.[9–11] These studies have promoted the development of ECLSS simulation technology, and played an important role in the research and development of ECLSSs.

Traditional dynamic simulation can put forward constructive opinions about system design and optimization. However, it is not so efficient as to simulate and test dynamic working performance because many high-precision models of subsystems need to be built and calibrated. In this case, the research period is too long to satisfy the requirements of rapid research and development for complex ECLSSs. For this type of complex system, it is urgent to find a new effective way.

Real-time simulation is a very effective way which considers hardware subsystems as virtual simulation models. Hence, hardware models do not need to be built at all, which will obviously save the research period and cut down the research expenditure at the same time.[12,13] For a complex ECLSS, its real-time simulation system is a very efficient way.

However, the real-time simulation technology has an inherent feature of fixed clock frequency.[14] The simulation time step should be fixed and set larger enough than the model solution time in each time step.[15] For this reason, current successful applications of real-time simulation are only some systems with a small number of models, such as some simulations for kinematics behaviors of trajectories[16] and motion control equations.[17] There are few real-time simulation applications about the ECLSS of a space station due to the following disadvantageous features.

(1) Coupling relationship between the pressure p and the mass flow rate $\dot{m}$.

In order to solve the values of p and $\dot{m}$ at any position in a fluid network, it needs to solve all the momentum and mass conservation equations of the flow network together. Hence, the number of equations will be huge if the fluid network system is a relatively complex one.[18,19]

(2) Time-varying characteristics of model parameters.

A change of the valve opening degree will lead to a change of the system eigenvalues correspondingly, which will easily lead to the instability of the simulation system. One way to overcome this issue is to adopt an implicit numerical integration method.

(3) A large amount and various types of subsystem models.

An ECLSS includes various components, and their mathematical models include a set of linear or nonlinear differential and algebraic equations. In addition, some models of regenerative components in the ECLSS are complex partial differential equations, such as the models of adsorption beds in the CDRS and the TCCS. In order to obtain their numerical solutions, they need to be transformed into a large number of ordinary differential equations.[20]

Therefore, the above disadvantageous features will undoubtedly and finally lead to a large amount of ordinary differential equations in the ECLSS simulation system. For time-varying real-time simulation, an implicit fixed time step numerical integration method with a better convergence performance is a preferred way.[21] However, its computational time in each step is much longer than that of an explicit numerical integration method, especially for a large complex system running on a PC cluster.[22] The computational time of an implicit method will dramatically increase with an increase of the number of ECLSS models, which cannot satisfy the real-time performance of the system. In contrast, an explicit numerical integration method has a higher computational efficiency in each step than an implicit one, but its simulation result may be not convergent for stiff systems.[23] If the simulation stability of the ECLSS system can be guaranteed very well, an explicit fixed step numerical integration method will be a good choice to solve a real-time ECLSS simulation system on a PC cluster.[24]

Oriented to the application of a real-time simulation system on a PC cluster, this paper mainly discuss a simulation method for ECLSSs using an explicit fixed step integral method. A simplified ventilation pipe network in the THCS of an ECLSS is taken as an example to discuss the models and numerical solution. The Geršgorin theorem[25] is adopted to analyze the stability of the large ordinary differential system. By analyzing the eigenvalue distribution of the simulation system, an adaptive operator is proposed to ensure the stability of numerical simulation. Based on the above study, a new modeling method is proposed to ensure the convergence of the system with the explicit numerical integration method. The simplified ECLSS example is used again to explain the application of the new modeling method and the adaptive operator. Furthermore, the simulation stability and simulation error are discussed. The studied simulation method can provide a good way to avoid the numerical divergence problem using the explicit fixed step numerical integration method and ensure the simulation efficiency of a complex real-time system on a PC cluster.