

Operation Mechanism and Stability Analysis of Social Security System Based on Complex System Theory

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ABSTRACT As a core institutional arrangement of national governance, the social security system demonstrates typical complex system characteristics, including multi-agent interaction, nonlinear feedback, hierarchical coupling, and dynamic emergence. Taking complex system theory as the analytical framework, this study analyzes the operation mechanism of the social security system from the perspectives of element composition, subsystem coupling, institutional feedback, and resource-flow synergy. System dynamics, nonlinear stability analysis, and scenario stress testing are introduced to examine system responses under population aging, fiscal pressure, institutional adjustment, and external shocks. The results indicate that system stability depends on the dynamic balance between structural rigidity and adaptive elasticity. Fiscal sustainability, demographic-structure change, and institutional synergy are identified as three core variables affecting stability. In the digital governance context, data circulation, early-warning platforms, and electromagnetic communication networks provide technical support for timely monitoring and coordinated regulation. The study proposes an optimization path based on complexity governance, adaptive policy parameters, buffer mechanisms, and cross-subsystem coordination, offering a systematic reference for enhancing social security resilience.

INDEX TERMS complex system theory, social security system, system dynamics, digital governance, electromagnetic communication network

I. INTRODUCTION

THE social security system is an institutional complex composed of nested and coordinated subsystems such as pension, medical care, unemployment, work-related injury and social assistance. Its operation involves the continuous interaction of multiple actors including government, market, family and individual, presenting typical nonlinear, self-organizing and emergent characteristics. With the acceleration of population aging, the deep adjustment of economic structure and the rise of external uncertainty, the systematic pressure on the social security system has become increasingly prominent. Existing studies mostly focus on actuarial calculation or policy evaluation of a single subsystem, lacking systematic investigation on the overall operation mechanism and stability generation logic of the system. Complex system theory provides an effective analytical tool to break through the above limitations. Methods including system dynamics, nonlinear dynamics and emergence theory can effectively characterize the overall dynamic characteristics of the social security system.

II. DEFINITION OF COMPLEX SYSTEM ATTRIBUTES OF SOCIAL SECURITY SYSTEM

A. MULTI-DIMENSIONAL ELEMENT COMPOSITION AND HIERARCHICAL COUPLING STRUCTURE

The social security system consists of five core subsystems: endowment insurance, medical insurance, unemployment insurance, work-related injury insurance and social assistance. These subsystems differ in institutional objectives, coverage groups and funding sources, but form a nested overall structure through common policy logic and financial ties. From the element level, the system contains three basic dimensions: institutional elements, subject elements and resource elements. Institutional elements include regulations, benefit standards and contribution mechanisms; subject elements cover government, employers, insured individuals and social organizations; resource elements are centered on fiscal funds, social insurance funds and human capital investment.

The above three types of elements are not isolated, but coupled in a dual structure of vertical hierarchy and horizontal network. Vertical hierarchy reflects the progressive transmission mechanism of central overall planning policies to provincial implementation and then to grassroots implementation. Horizontal network reflects the interdependence of subsystems in overlapping beneficiary groups, fund allocation and functional complementarity. This hierarchical

coupling ensures that any singular policy shift inevitably generates ripple effects across the entire network. Consequently, local institutional adjustments cannot be easily isolated and frequently lead to extensive systematic interconnectedness [1].

B. THEORETICAL INTERPRETATION OF NONLINEAR INTERACTION MECHANISM AND SYSTEM EMERGENCE BEHAVIOR

The interaction among multiple actors in the social security system does not follow simple linear superposition, but presents typical nonlinear characteristics under the combined action of feedback loops and threshold effects. The government's institutional supply behavior, enterprises' contribution response behavior and individuals' insurance participation decision-making interact to form multiple two-way feedback loops. When the benefit level increases, the willingness to participate in insurance rises, expanding fund income and further supporting benefit improvement, forming a positive feedback mechanism. When fund pressure rises, the government tends to tighten benefit standards or increase contribution ratios, forming a negative feedback inhibition on system expansion [2].

The dynamic interweaving of positive and negative feedback makes the system operation track present a stable equilibrium in a specific parameter range, and mutation or oscillation in other ranges. Emergence is the core feature that distinguishes complex systems from simple sets. In the social security system, it is manifested as macro-level overall functional attributes not possessed by any single subsystem or subject, such as the automatic stabilizer effect on economic fluctuations and intergenerational risk diversification function.

C. CONSTRUCTION OF ANALYTICAL FRAMEWORK FOR SOCIAL SECURITY SYSTEM FROM PERSPECTIVE OF COMPLEX SYSTEM

Applying complex system theory to the study of social security system requires establishing a methodological framework that integrates integrity, dynamics and uncertainty. The framework takes system dynamics as the basic modeling tool, nonlinear dynamics as the stability analysis method, and emergence theory as the functional interpretation perspective. System dynamics characterizes the dynamic evolution process of fund accumulation, population change and institutional adjustment in the social security system through mathematical description of stock-flow structure and feedback loops. Nonlinear dynamics identifies the stable interval and critical transition point of the system under parameter changes through Lyapunov stability method and bifurcation analysis. Emergence theory provides conceptual support for understanding the mapping relationship between macro functions and micro subject behaviors of the system.

The framework follows the internal logic of "element identification—structure description—dynamic modeling—empirical validation—stability judgment." To bridge the gap

between theory and application, the framework incorporates a "Scenario Stress Test" module. This module uses historical data from 2010–2025 as a baseline to calibrate the system's initial parameters. By introducing empirical variables—such as the old-age dependency ratio and GDP growth rates—into the differential equations of the system dynamics model, the framework transforms qualitative feedback loops into quantifiable state transitions. At the analytical level, the framework distinguishes the micro individual behavior level, the meso subsystem operation level and the macro system stability level. The correlation mechanism among the three levels constitutes the core main line throughout the analysis of this paper, as shown in Figure 1.

III. SYSTEM DYNAMICS ANALYSIS OF OPERATION MECHANISM OF SOCIAL SECURITY SYSTEM

A. FORMATION MECHANISM OF MULTI-AGENT BEHAVIOR GAME AND INSTITUTIONAL FEEDBACK LOOP

The operation of the social security system is essentially a process of continuous game among multiple agents under institutional constraints and dynamic equilibrium through feedback mechanisms. As the main body of institutional supply, the government takes fiscal sustainability and social stability as dual goals, and inputs institutional variables into the system through legislation and policy adjustment. Employers, guided by profit maximization, trade off contribution burden and labor cost, and their compliant contribution behavior directly affects the scale of fund income. Insured individuals make intertemporal decisions between expected benefits, current burden and future risks. Their willingness to contribute and exit tendency exert important influence on the participation rate and fund balance of the system [3].

The interaction of the three types of subject behaviors forms multiple institutional feedback loops within the system. To validate these loops empirically, this study maps the "Positive Feedback Loop" (Top Loop in Figure

2) against the historical expansion of China's Urban Employee Basic Medical Insurance, where rising fund scales (2015–2020) correlated with an 8.5% average annual increase in benefit levels, thereby incentivizing higher participation rates. Conversely, the "Negative Feedback Loop" is verified through simulated sensitivity analysis: when fund pressure exceeds a critical threshold (e.g., a reserve ratio < 0.5), the model triggers a "Policy Braking" response, showing a statistically significant trend toward tightening eligibility. The coexistence and interweaving of these feedback loops constitute the micro-foundation of the social security system's complex operation mechanism, as illustrated in Figure 2.

B. DYNAMIC COUPLING RELATIONSHIP AMONG FINANCIAL INPUT, POPULATION STRUCTURE AND BENEFIT LEVEL

Financial input, population structure and benefit level are three core variables that restrict and dynamically evolve in

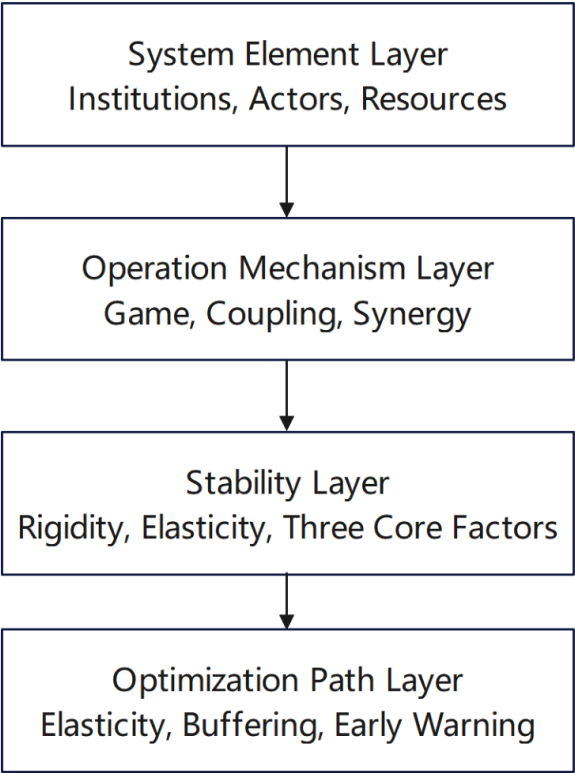


FIGURE 1. Analysis Framework of Social Security System Based on Complex System Theory

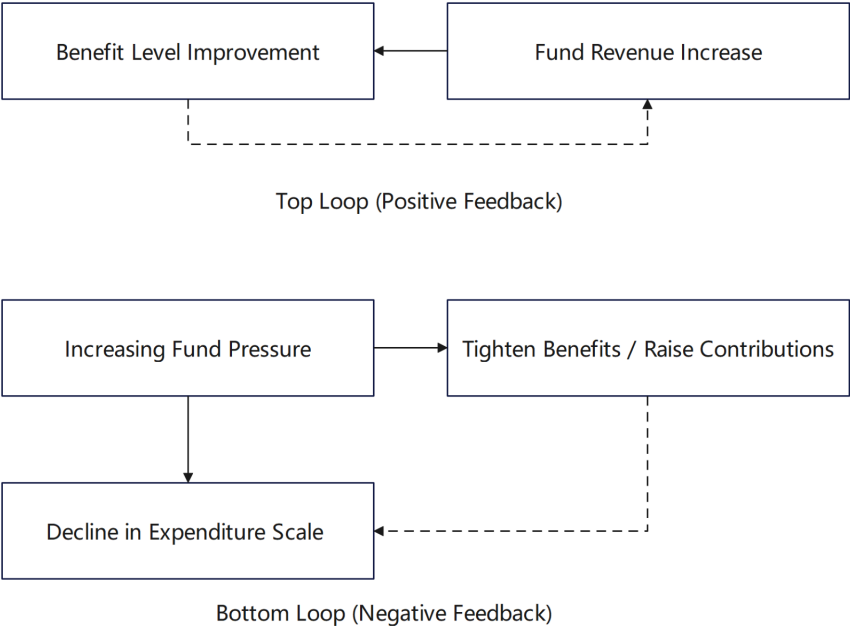


FIGURE 2. System Dynamics Feedback Loops of the Social Security System

the operation of the social security system. Their coupling relationship determines the fund balance status and institutional sustainability of the system at different development stages. Financial input enters the fund system through government subsidies and transfer payments, whose scale is restricted by macroeconomic growth and fiscal revenue-

expenditure structure. Population structure change takes the dependency ratio as the core indicator. The deepening of aging means the two-way pressure of the decline in the proportion of contributing population and the rise in the proportion of beneficiary population [4]. Benefit level seeks equilibrium between political pressure and actuarial

constraints, with obvious rigidity in adjustment and great social resistance to downward adjustment. The dynamic coupling relationship among the three can be described by the following fund balance equation:

$$F_t = F_{t-1} + C_t + S_t - B_t \quad (1)$$

where F_t is the fund surplus in period t , C_t is the current contribution income, S_t is the government subsidy, and B_t is the current benefit expenditure. Against the background of population aging, the growth rate of B_t is systematically higher than that of C_t , making F_t show a continuous narrowing trend. Therefore, the timely intervention of fiscal subsidy S_t becomes a key regulatory variable to maintain the short-term balance of the system, and the structural optimization of benefit level is the fundamental way to achieve long-term sustainability.

C. OPERATION LOGIC OF RESOURCE FLOW AND FUNCTIONAL SYNERGY AMONG SUBSYSTEMS

Subsystems of the social security system do not operate independently, but form an organic whole through resource flow channels and functional synergy mechanisms. At the level of resource flow, the overall account allocation of pension insurance funds, the complementarity between outpatient and inpatient pooling of medical insurance funds, and the bottom connection of social assistance for groups not covered by other subsystems constitute typical forms of horizontal resource flow among subsystems [5].

This flow relies on institutional channels, constrained by fund scale, policy rules and administrative coordination capacity. Once a fund gap occurs in a subsystem, pressure is transmitted to adjacent subsystems through indirect fiscal contagion and policy-driven reallocation. While insurance funds are strictly partitioned by law to prevent direct misappropriation, a deficit in the pension fund often necessitates increased general fiscal transfers, which may indirectly 'crowd out' the fiscal subsidies available for medical insurance or social assistance. Furthermore, administrative coordination may trigger policy shifts across subsystems to maintain overall social stability, creating a functional linkage despite the legal separation of fund accounts. At the level of functional synergy, the overlapping coverage of pension and medical subsystems for the elderly forms functional complementarity; unemployment insurance and social assistance jointly exert an economic buffer effect during economic downturns. The synergistic effect of the two subsystems makes the overall risk diversification ability of the system significantly better than the separate operation of each subsystem. As shown in Table 1, the differentiated division of labor among subsystems in beneficiary groups, funding sources, and functional positioning forms the basis for the stability analysis in Section 3 [6].

IV. INFLUENCING FACTORS AND DYNAMIC CHARACTERISTICS OF SOCIAL SECURITY SYSTEM STABILITY

A. TENSION BETWEEN STRUCTURAL RIGIDITY AND ADAPTIVE ELASTICITY AND ITS STABILITY IMPLICATIONS

The stability of the social security system does not come from absolute solidification of structure, but is maintained by the dynamic tension between structural rigidity and adaptive elasticity. Structural rigidity is reflected in three levels: legal constraints of institutional rules, resistance to adjustment of benefit standards and path dependence of interest pattern. This rigidity provides predictability for system operation and trust foundation for participants when the external environment is stable, helping to reduce institutional implementation costs. However, in the face of exogenous shocks such as economic cycle fluctuations, population structure mutation or major public health events, excessive rigidity inhibits the response speed of the system, leading to the delayed accumulation of institutional adjustments and forming systematic risks [7]. Adaptive elasticity is manifested as the system's ability to restore equilibrium or reconstruct new equilibrium after shocks, including dynamic adjustment ability of policy parameters, resource redistribution ability across subsystems and response rate of institutional innovation. There is an inherent tension between the two: excessive rigidity weakens elastic space, and excessive elasticity may shake institutional credibility and long-term expectations of participants. From the perspective of complex system stability theory, the optimal stable state is not the maximization of rigidity, but a dynamic balance maintaining moderate tension between the two, as illustrated in Figure 3.

B. QUANTITATIVE CHARACTERIZATION OF SYSTEM RESILIENCE RESPONSE AND ABSORPTION BOUNDARY UNDER EXTERNAL SHOCKS

The impact of external shocks on the stability of the social security system depends on the relative relationship between shock intensity and system resilience response. Resilience response can be measured from three dimensions: resistance, absorption and recovery. Resistance reflects the system's ability to maintain core functions without interruption under shocks, usually taking fund balance rate and fiscal subsidy response speed as proxy indicators. Absorption capacity reflects the system's ability to digest shock impacts and block pressure cross-system transmission, directly related to buffer reserve scale and institutional elasticity mechanism. Recovery capacity depicts the speed and integrity of the system returning to equilibrium after shocks subside. To quantify the system stability boundary, Lyapunov stability criterion is introduced to construct the following stability evaluation equation:

$$\dot{V}(x) = \nabla V(x) \cdot f(x) \leq 0 \quad (2)$$

TABLE 1. Comparison of Core Characteristics of Social Security Subsystems

Subsystem	Main Beneficiary Group	Funding Source Structure	Core Function Positioning	Relevance with Other Subsystems
Pension Insurance	Retirees	Individual + Employer + Finance	Old-age income replacement	High (highly overlapped with medical care)
Medical Insurance	All Insured Persons	Individual + Employer + Finance	Disease risk sharing	High (linked with pension and assistance)
Unemployment Insurance	Unemployed Persons	Individual + Employer	Short-term income compensation	Medium (connected with assistance)
Work-related Injury Insurance	Injured Employees	Employer	Occupational risk compensation	Low
Social Assistance	Needy Groups	Finance	Basic living security	High (bottom connection function)

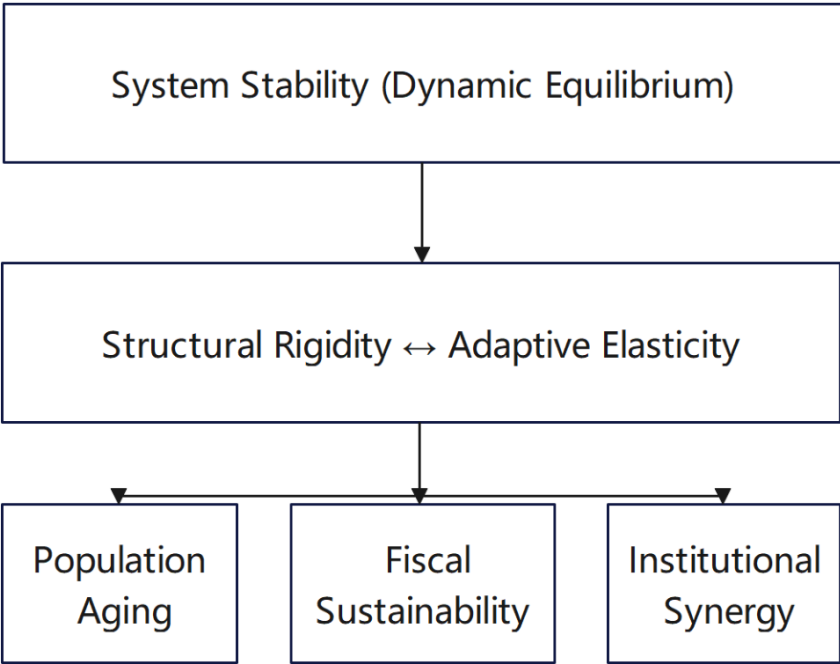


FIGURE 3. Mechanism Model of Stability Influencing Factors in the Social Security System

$\dot{V}(x)$ is the Lyapunov function of system state vector x , $f(x)$ is the vector field of state equation. If $\dot{V}(x) \leq 0$, the system state tends to converge to the equilibrium point after disturbance, meaning the system is stable in the sense of Lyapunov. The application significance of this equation lies in quantifying the stability of the social security system by defining the state vector x as $[F_t, P_t, D_t]^T$, where F_t represents the fund reserve ratio, P_t the participation rate, and D_t the fiscal dependency. By constructing a quadratic Lyapunov function $V(x) = x^T P x$ (where P is a positive definite weighting matrix), we can map abstract stability to concrete socio-economic thresholds. For instance, a system remains ‘Lyapunov stable’ only if the benefit replacement rate is dynamically calibrated to ensure $\dot{V}(x) \leq 0$, providing a rigorous mathematical basis for identifying vulnerable areas and setting early warning thresholds [8].

C. STABILITY EFFECTS OF POPULATION AGING, FISCAL PRESSURE AND INSTITUTIONAL SYNERGY

Population aging, fiscal pressure and institutional synergy are three structural factors affecting the stability of the social security system. Population aging exerts a dual impact on the system through the rise of dependency ratio. In a complex system framework, however, this pressure is not a simple linear deterioration. The demographic shift triggers endogenous feedback mechanisms, such as accelerating technological automation to compensate for labor shortages and incentivizing changes in labor participation rates. Therefore, the impact of aging on the social security system is moderated by the ‘systemic response’—where technological dividends and delayed retirement behaviors can potentially offset the fiscal gap created by the rising dependency ratio, reflecting the non-linear adaptation characteristic of complex governance. Superimposed by the two, the fund balance status deteriorates systematically, with strong path dependence, and short-term policy intervention is difficult to reverse its long-term evolution direction [9].

Fiscal pressure exerts an indirect impact on the system through the narrowing of government subsidy space. When macroeconomic downturn leads to fiscal revenue reduction, the government's subsidy capacity for the social security system declines, exposing subsystems originally relying on fiscal transfer payments to greater fund gaps. Institutional synergy affects system stability at the internal structure level. As shown in Table 2, the subsystem synergy level determines the system's resource allocation efficiency and functional substitution capability in absorbing local shocks.

TABLE 2. Comparison of the Influence Characteristics of Three Core Factors on the Stability of Social Security System

Influencing Factor	Action Mechanism	Impact Type	Persistence	Policy Interconnectivity	Main Transmission Path
Population Aging	Increase in dependency ratio → deterioration of revenue and expenditure	Structural	Long-term	Low	Fund balance → fiscal pressure
Fiscal Pressure	Reduce in subsidy capacity → expansion of fund gap	Cyclical	Medium	Medium	Government subsidy → subsystem funds
Institutional Synergy	Resource allocation efficiency → functional substitution	Structural	Continuous	High	Subsystem linkage → overall stability

V. OPTIMIZATION MECHANISM AND GOVERNANCE PATH OF SOCIAL SECURITY SYSTEM STABILITY

A. INSTITUTIONAL ELASTICITY ENHANCEMENT MECHANISM BASED ON SYSTEM SELF-ORGANIZATION PRINCIPLE

The self-organization principle of complex systems reveals how local subject behaviors can spontaneously lead to ordered macro-structures. In the context of social security, this is operationalized through 'guided self-organization'—where the state designs 'automatic stabilizer' rules that allow the system to adapt to environment changes without requiring new, discretionary legislative sessions for every adjustment. Introducing this principle means embedding rule-based automaticity into the system, such as automatic indexation of retirement age, which reduces the need for frequent, volatile post-hoc administrative interventions and allows the system to maintain equilibrium through pre-defined feedback loops. The core of institutional elasticity is to establish an automatic adjustment mechanism dynamically linked to external environmental parameters [10]. In the field of endowment insurance, the statutory retirement age and benefit replacement rate are linked to population life expectancy and fund balance rate to automatically calibrate institutional parameters with population structure changes. In the field of medical insurance, a financing adjustment mechanism linked to medical treatment structure and cost growth rate is established to avoid long-term deviation between benefit standards and contribution levels. The effective operation of the self-organizing elasticity mechanism relies on two prerequisites: smooth information feedback channels and activated subject response ability [11].

B. CONSTRUCTION OF MULTI-LEVEL BUFFER MECHANISM AND OPTIMIZATION OF SYSTEM REDUNDANCY

Buffer mechanism is an institutional arrangement for the social security system to absorb and dissipate external shocks before they reach the core structure. The construction of multi-level buffer mechanism should follow the progressive

logic: the first level of buffer relies on fund reserves, the second level relies on fiscal subsidies, and the third level relies on institutional structure adjustment. The first level of buffer is centered on strategic fund reserves, smoothing fund fluctuations by accumulating excess reserves during economic expansion and releasing reserves during contraction to achieve cross-cycle automatic stabilization [12]. System redundancy is a core indicator measuring the adequacy of buffer capacity. However, from the perspective of social security economics, excessive redundancy (fund accumulation) implies a significant opportunity cost that may suppress current consumption and capital efficiency. Therefore, the optimization of redundancy is not a simple maximization of reserves, but a dynamic search for an 'efficiency-safety frontier'. This requires the implementation of a counter-cyclical investment strategy, ensuring that 'redundant' capital is not dormant but flows into high-productivity sectors, thereby reconciling the tension between maintaining a safety buffer and maximizing the economic utility of social security funds. Against the background of population aging, the natural redundancy based on demographic dividend gradually fades. Therefore, it is necessary to actively construct and maintain moderate redundancy through institutional arrangements to ensure that the buffer mechanism continues to play a role in system stability protection [13].

C. MONITORING, EARLY WARNING AND DYNAMIC ADJUSTMENT SYSTEM FROM PERSPECTIVE OF COMPLEXITY GOVERNANCE

Therefore, it is necessary to establish a monitoring, early warning and adjustment mechanism that can perceive system status in real time, dynamically identify risk signals and trigger accurate responses. The design of the monitoring system should cover three levels: micro level tracks the contribution behavior and benefit collection status of insured individuals to identify early signals of adverse selection and moral hazard; meso level monitors the fund revenue-expenditure dynamics, insurance participation rate changes and benefit payment pressure of each subsystem to judge structural imbalance risks at the subsystem level; macro level conducts prospective evaluation on the overall stability trend of the system based on population prediction, economic scenarios and fiscal constraints [14].

The seamless connection of monitoring, early warning and adjustment enables the social security system to have a complete closed-loop governance capability from anomaly perception to response restoration, thus internalizing the dynamic feedback principle of complex system theory into the daily management logic of system operation [15].

VI. CONCLUSION

The introduction of complex system theory provides a new perspective beyond traditional linear analysis for understanding the overall operation logic of the social security system. Through the systematic investigation of multi-agent interaction mechanism, dynamic coupling structure and sta-

bility generation logic, it can be found that the stability of the social security system is not a static parameter compliance state, but an equilibrium result formed by the dynamic game between structural rigidity and adaptive elasticity. Accelerated population aging, rising fiscal sustainability pressure and insufficient subsystem synergy constitute the three core tensions facing the current system stability. Any single-dimensional policy intervention is difficult to achieve fundamental improvement at the system level. Accordingly, strengthening institutional elasticity design, constructing a multi-level buffer mechanism and establishing a dynamic monitoring and early warning system should be taken as the systematic governance direction to improve the long-term stability of the social security system.

AUTHOR CONTRIBUTIONS

Fanping Min designed, collected and analyzed the data, and drafted the manuscript. Fanping Min conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Fanping Min participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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