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CONTENTS

Study on High-quality Development Path of Student Party Members in Higher Vocational Colleges

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Abstract: The development of student party members in colleges and universities is an important part of the party building work and an important basis for the construction of party organizations, but at present, the development of student party members in higher vocational colleges faces many realistic difficulties:(1) The development system of student party members is not perfect; (2) Party member development process and file management are not standardized enough; (3) Party member training is not scientific enough; (4) Party cadres' skills are not professional enough. This paper puts forward the innovation mechanism of the high quality development system of student party members in higher vocational colleges:(1) Innovative data-based management mechanism; (2) Innovation and modernization training mechanism; (3) Innovation policy coordination guarantee mechanism.
Keywords: Higher vocational colleges; Student party members; Development path

1. INTRODUCTION

The development of student party members in colleges and universities is an important part of the party building work and an important basis for the construction of party organizations. The accumulation of student party members is not the only way to solve the problem of the strength reserve of the Communist Party of China. Priority should be given to formulating quality standards for the development of student party members in higher vocational colleges to guide the development of talents with firm ideals and beliefs needed by the Party and the government in colleges and universities. Only in this way can we effectively alleviate the problem of talent reserve within our Party. In 2020, the General Office of the Central Committee of the Communist Party of China issued the "Rules for the Work of the Communist Party of China to develop Party Members"[1], which made clear requirements for the education and training of university student Party members, but they still face severe challenges in the concrete practice process. Some college students have incorrect motives for joining the Party, do not pay attention to the training and investigation of party members' development process, and do not pay attention to the training of already developed party members. The lack of political acumen of some student party members, the short academic system of junior college, the links of party membership, the low quality of party cadres, and the lack of detailed understanding of the procedures of student party membership have seriously affected the quality of the development of student party members[2-7].

2. THE IMPORTANCE OF HIGH QUALITY DEVELOPMENT RESEARCH OF STUDENT PARTY MEMBERS IN HIGHER VOCATIONAL COLLEGES

(1) It is helpful to grasp the value orientation and behavior of student party members in higher vocational colleges under the conditions of the new era

Helps to expand the academic vision cultivated by the new era. Taking the education and training of student party members as the research object in the education mechanism of colleges and universities is helpful to grasp the value orientation and behavior of student party members in higher vocational colleges in the new era, provide scientific guidance for the education and training of student party members, and explore their special education value, which not only reflects innovation, but also has certain methodological significance.

(2) It is helpful to scientifically grasp the new situation, new characteristics and new situation of the development of college student party members under the background of the new era

It is helpful to deepen the understanding of the subject research of ideological and political education for college students. In the face of the profound changes in the situation at home and abroad, paying attention to the ideological and political education of student party members has distinct characteristics of The Times under the new historical conditions, which conforms to the essential requirements of academic research to keep pace with The Times, and is helpful to scientifically grasp the new situation, new characteristics and new situation of the development of student party members in colleges and universities under the background of the new era. To provide practical guidelines for the Party and the government to scientifically understand, grasp and train the socialist builders and successors;

(3) It is helpful to further improve the theoretical system of quality management for the development

of student party members in higher vocational colleges

It is helpful to further improve the theoretical system of quality management for the development of student party members in higher vocational colleges. The development quality of student party members determines the quality of outstanding students and cadres in a college, is an important part of the ideological and political construction of colleges and universities, and has important value for higher vocational colleges to improve the working methods of party members development and implement the requirements of party members development. It is helpful to find a breakthrough for the high-quality development of university student party members from the perspective of the development process, time node and training education of party members, and give practical guidelines and policy suggestions for the problems encountered in the development process of student party members, so as to further promote the improvement of the development quality of university student party members.

3. RESEARCH STATUS AT HOME AND ABROAD

Due to the special national conditions of our country, the research on the development of student party members is mainly concentrated in China, and the research on the development of student party members mainly includes the following three aspects: The first is the sorting and analysis of the problems and loopholes in the development of student party members, which is also the most relevant research field. Scholars have pointed out the problems encountered in the development of student party members in universities and countermeasures. Such as the contradiction between the training cycle of student party members in higher vocational colleges and the academic system of Fan[8], the increasing number of developing party members, the new challenges facing the quality of student party members, the weak construction of the team of full-time party workers, insufficient staffing, the deviation of the motivation of some students to join the Party, the imperfect training and investigation mechanism, and the insufficient role of training contacts in education and guidance, etc. And put forward five countermeasures to strengthen the training and education stage in the process of party members' development. Zhang[9], in view of the problems existing in the development of university student party members, such as piggy-back on the organization, objectification of the subject and instrumentalization of the purpose, proposed to standardize organizational life, strengthen organizational functions, implement the strategy of "materialism", adhere to the standards of political literacy, adhere to the principle of seeking truth from facts, and overcome the formalistic style. The second is the exploration of the working mode of student party members' development. For example, Wang Jian, Mu Lin et al. developed and designed the whole-process management information system for the development of university student party members by means of information technology and based on the design concept of "mass visualization". The system, in the form of a combination of computer terminal and mobile phone terminal, includes various contents of the development of party members and provides whole-process management, guidance and services for the development of party members. It has greatly promoted the quality and level of "smart Party building"[10]. The third is to carry out a detailed study on a specific work of the development of student party members. For example, Ning Qian conducted a survey on the selection of student party members in 8 representative universities in Yunnan Province. It is found that the active members of the Party have low enthusiasm about whether they can become development objects, insufficient understanding of the selection procedure, single form of democratic selection and recommendation, vague selection criteria, insufficient scientific and reasonable selection procedures, and low degree of mobilizing all parties to participate in the selection, and put forward the evaluation principle of "four combinations". Construct the "three sets of mechanisms" of the examination system, the quantitative score evaluation system, and the defense system[11].

To sum up, the academic community has carried out a multifaceted analysis of this issue, which provides valuable reference for the research of this topic, but there are still some problems to be solved: First, from the perspective of research, the existing researches mainly think from the perspective of pedagogy, and rarely study how to organize, coordinate and control student party members to improve their quality in the development process from the perspective of management disciplines; Second, in terms of research content, the existing research has a more detailed discussion on the development process of student party members and the problems arising from it, but has not formed a systematic understanding of the root cause and mechanism of the problems, and lacks a scientific analysis of the development status of student party members. Third, in terms of research methods, the existing research results mainly use qualitative research and case studies, lack extensive research basis and statistical analysis, and the suggestions and methods proposed lack big data support and concrete practicability, and are mostly from a single disciplinary perspective, with less emphasis on interdisciplinary research methods.

4. THE REALISTIC DILEMMA OF THE DEVELOPMENT OF STUDENT PARTY MEMBERS IN VOCATIONAL COLLEGES

(1) The development system of student party members is not perfect

In some colleges and universities, the evaluation

system of the periodic development stage of student party members lacks clear indicators. The evaluation of student party members' party spirit consciousness, vanguard model role and mass base has not been in-depth and detailed. The participation, autonomy and sense of identity of student party members have been ignored, such as the exercise of party spirit, the role model and the evaluation of teachers and students.

(2) Party member development process and file management are not standardized enough

At present, the party member development process and file management standards vary from place to place, resulting in confusion in the process of party member development, resulting in loopholes in party member file materials, and many problems in the process of party organization relationship transfer.

(3) Party member training is not scientific enough

The small number of student party members in higher vocational colleges leads to easy neglect in the process of training and education, including the lack of training venues, funds and teachers and other resources, which further leads to the lazy performance of daily training of student party members, and it is difficult to meet the current demand for student party members in professional training of party building.

(4) Party cadres' skills are not professional enough

In the process of selecting and training party affairs talents, party organizations in some higher vocational colleges generally tend to emphasize professional skills and despise party affairs management. Most party cadres are not from professional backgrounds, lack of theoretical knowledge of party building and outdated working methods, so the professional ability of party cadres urgently needs to be enhanced.

5. HIGHER VOCATIONAL COLLEGE STUDENT PARTY MEMBERS HIGH-QUALITY DEVELOPMENT SYSTEM INNOVATION MECHANISM

(1) Innovate the data-based management mechanism

Through big data innovation, the party member development process and file management are standardized, party member training, party member evaluation and other processes are visualized through the online platform, and archives are retained.

(2) Innovate and modernize training mechanisms

Innovate the content and form of modern training, such as organizing red theme salons, reports, knowledge competitions, selection of role models around and other normal party member education activities, combining modern party building knowledge in content, advancing with The Times, ignites students' enthusiasm and initiative at the ideological level through innovation in training forms and content, and creates a positive learning atmosphere.

(3) Innovation policy coordination guarantee mechanism

Strengthen the management system of party cadres, especially organization members, and create a group of professional student party building teams with excellent literacy, outstanding ability, familiarity with business and strict discipline, so as to promote the development of party building work in a more professional direction. Refine the reward and punishment measures, implement the performance management of college students' party building work, and maximize the dedication of party staff and the enthusiasm for innovation and entrepreneurship.

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Research on the Employment Power Enhancement Strategies for College Students in Finance and Economics under the Background of Digital Economy

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Abstract: Currently, the digital economy is gradually becoming the core driving force and key engine for promoting high-quality economic development in China. Against this backdrop, College Students in Finance and Economics Universities in China face numerous opportunities and challenges in employment. Emerging fields such as financial technology and blockchain provide diverse employment opportunities, but also bring about issues such as skill updates, job displacement, and intensified competition. Through analysis, this paper finds that students from finance and economics universities have advantages in terms of professional knowledge, data analysis capabilities, and adaptability. However, they also face shortcomings such as intense homogenized competition, insufficient practical experience, and lack of innovation ability. Combining the current development trends of the digital economy, this paper proposes countermeasures and suggestions from aspects such as promoting supply-side structural reforms in China's higher education system, improving the "college-government-enterprise-society" integrated talent cultivation framework, and stimulating the internal motivation of college students in finance and economics universities for employment. These suggestions provide theoretical support and practical guidance for enhancing the employability of university students from finance and economics colleges.

Keywords: Digital Economy; Finance and Economics Universities; University Students; Employability

1. INTRODUCTION

Under the impetus of the digital wave, the digital economy has become the core engine of global development. Especially in China, its rapid development has become a key driver of high-quality economic growth. According to the China Academy of Information and Communications Technology's “China Digital Economy Development Research Report (2024) [1],” China's digital economy reached a scale of 53.9 trillion yuan in 2023, growing by 7.39% year-on-year, contributing 66.45% to GDP growth. The digital economy is characterized by data as its core, information networks as its carrier, and information technology as its driver. It features high integration, platformization, and globalization [2]. With government policy support and participation from all sectors of society, the digital economy has reshaped traditional industrial patterns, improved resource allocation efficiency, promoted the rise of emerging industries, and become an important support for China's stable economic growth and global competitiveness. The vigorous development of the digital economy has injected new vitality into the job market, giving birth to a large number of emerging professions and positions, and also driven the expansion of employment scale, optimization of structure, and improvement of quality. This trend has had a profound impact on the employment of university students majoring in finance and economics, broadening their career choices while also placing higher demands on their digital skills and interdisciplinary abilities.

2. OPPORTUNITIES AND CHALLENGES FOR EMPLOYMENT OF COLLEGE STUDENTS IN FINANCE AND ECONOMICS UNIVERSITIES IN CHINA UNDER THE BACKGROUND OF THE DIGITAL ECONOMY

Finance and economics universities in China, with finance and economics disciplines at their core, emphasize practicality, internationalization, and employment orientation, forming distinctive characteristics in curriculum design, teaching models, and campus culture. For young students in these universities, the digital economy era presents both new challenges and vast development opportunities.

On one hand, the vigorous development of the digital economy has brought multiple opportunities for employment to college students in finance and economics universities. In the era of the digital economy, emerging industries and job roles are continuously emerging. For instance, with the rise of green finance and ESG investments, rapid advancements in fields such as fintech, digital payments, and blockchain have led to an increasing

demand for digital-related positions, creating a wealth of job opportunities for students in finance and economics. At the same time, the skill requirements for jobs are becoming more diversified, with a growing preference for interdisciplinary talents who possess both financial expertise and digital capabilities. Additionally, the blurring of industry boundaries offers students in finance and economics more flexible and diverse career paths, including cross-industry employment, entrepreneurship, freelancing, and global job opportunities.

On the other hand, the acceleration of digitalization has also posed multiple challenges for the employment of college students in finance and economics universities, including skill updates, intensified competition, and job displacement. "The Future of Jobs Report 2025" released by the World Economic Forum, based on a survey of over 1,000 companies across 22 industries and 55 economies, emphasizes that artificial intelligence and big data, networks and cybersecurity, and technological literacy are expected to be the top three fastest-growing skills [3]. With the changing social demands and the driving force of emerging technologies, the mastery of digital skills such as data analysis, programming, artificial intelligence, and cybersecurity, as well as the requirement for interdisciplinary knowledge, has increased. However, the traditional curriculum system in finance and economics universities may not effectively cover these areas.

Through statistical analysis of recruitment information in the job market over the past two years, it has been found that the demand for finance and economics talent in the digital economy is primarily concentrated in roles such as digital management and operational services, as well as digital research, mostly distributed within the field of industrial digitalization. These positions often require a combination of "finance + digital" skills, reflecting a compound talent demand [4]. This places higher demands on finance and economics universities, necessitating a focus on digital skills to enhance their professional support capabilities for students in the context of the digital economy. Additionally, to improve competitiveness and achieve sustainable development, many traditional industries are undergoing digital transformation, which intensifies job market competition. Repetitive and mechanical tasks are gradually being replaced by automation technologies. This requires students to keep pace with the demands of the digital economy, strengthen their digital skills, broaden their employment perspectives, accumulate interdisciplinary knowledge in "digital +" fields, promote the deep integration of finance and technology, enhance practical and innovative capabilities, and explore career paths that suit their individual strengths, thereby better adapting to the rapidly changing societal needs.

3. CURRENT STATUS AND ISSUES OF EMPLOYMENT FOR COLLEGE STUDENTS IN FINANCE AND ECONOMICS UNIVERSITIES IN CHINA UNDER THE BACKGROUND OF DIGITAL ECONOMY

The employment of college students is closely tied to the well-being of millions of households and serves as a core component of the Chinese government's "stabilizing employment" policy. Driven by the rapid development of digital technologies, the deep integration of algorithms and media in society has not only transformed the lifestyles of college students, shaping their unique thinking patterns, behavioral habits, and cultural characteristics, but has also endowed them with distinct group traits, such as information sensitivity, personalized expression, instant feedback, and participatory co-creation. At the same time, it has imposed new and higher demands on their employability. Employability refers to the combination of knowledge, skills, values, and core competencies that directly influence the likelihood of employment and career success for college students [5]. Enhancing employability is directly related to students' employment rates and the quality of their actual employment [6]. A better understanding and recognition of the group traits and employment characteristics of young students in finance and economics universities under the digital economy is a prerequisite and key to improving employability.

From a practical perspective, college students in finance and economics universities possess distinct employment traits, such as solid professional knowledge, outstanding data analysis capabilities, strong communication and teamwork skills, and a high degree of flexibility and adaptability in rapidly changing social environments. In response to "liquid modernity [7]," they are able to embrace change, build resilient identities, and establish fluid relational networks. These traits enable them to better adapt to the demands of the digital economy era and integrate more quickly into digital work environments. Many students are proficient in using data analysis tools and social media platforms, and possess a multidisciplinary, composite knowledge structure. These advantages give them a competitive edge in the job market and contribute to the overall enhancement of employability.

Under the backdrop of the digital economy, the employment challenges faced by college students in finance and economics universities exhibit complex and multidimensional characteristics. Although overall employability has improved, significant gaps remain in certain areas, alongside intensifying homogeneous competition and internalization issues. On one hand, students have a strong demand for resources and support during their job preparation process, hoping to enhance their competitiveness and career planning capabilities through external assistance. On the other hand, due to limited

resources, homogeneous competition, constraints in career guidance, and psychological pressures, some students lack motivation to participate in career counseling due to factors such as "self-consumption" within the group, low self-efficacy, learned helplessness, and the lack of immediate rewards [8]. Additionally, students commonly face issues such as overly high income expectations, rigid employment mindsets, insufficient practical experience, and a lack of innovative exploration. Employability is also significantly influenced by factors such as gender, educational background, and family circumstances. Students with higher education degrees, urban backgrounds, and those in leadership roles often demonstrate stronger employability due to greater access to resources and practical opportunities, while rural students and those with lower educational qualifications tend to lag behind in social practice and innovation capabilities [9]. Therefore, despite the abundant opportunities offered by the digital economy, college students still need to comprehensively enhance their overall competencies, particularly in practical and innovative abilities, to better adapt to the complex and ever-changing job market.

4. STRATEGIES TO ENHANCE THE EMPLOYABILITY OF COLLEGE STUDENTS IN FINANCE AND ECONOMICS UNIVERSITIES IN CHINA UNDER THE DIGITAL ECONOMY BACKGROUND

In recent years, the scale of Chinese university graduates has been increasing annually. According to statistics, the number of graduates from Chinese universities in 2025 is expected to reach 12.22 million, an increase of 430,000 compared to the previous year [10]. Due to the combined impact of domestic and international macroeconomic downward pressures and multiple factors, the employment situation for Chinese university graduates has become more severe and complex. At the same time, faced with the opportunities and challenges brought by the digital economy, enhancing employability has become a key factor in helping students achieve high-quality employment and career aspirations. It is also one of the important strategic goals for international organizations and governments worldwide in the field of higher education.

(1) Promote structural reforms in the supply side of higher education to enhance the ability of college students in finance and economics universities to adapt to employment in the digital economy era

First, guided by digital innovation, optimize talent cultivation models. Lifelong learning and interdisciplinary knowledge integration will become key to future career development. Universities should adjust and innovate their program offerings, creating specialized programs that meet digital demands. Build an interdisciplinary curriculum integration system, add digital technology programs such as artificial intelligence, big data, and blockchain, and expand the supply of talent in digital fields. Optimize the cultivation process, improve the employability enhancement system, develop students' "cognitive intelligence [11]," enhance employment matching, and optimize the labor market structure. At the same time, establish a dynamic feedback mechanism from the demand side to the supply side [12]. Through career development tracking, employer feedback, and dynamic adjustments, improve the employment quality evaluation system to ensure it is scientific, comprehensive, and dynamic, accurately reflecting graduates' employment status and promoting the close integration of talent cultivation with societal needs.

Second, build a professional career guidance team and strengthen targeted guidance. Guided by student needs and closely aligned with the trends of the digital economy, systematic training should be conducted to enhance the career guidance and market development capabilities of employment staff at both university and college levels, including class advisors, counselors, and mentors. This will create a collaborative and interconnected employment support system, helping students establish a scientific outlook on career development and employment, improve their adaptability to digitalization, and transform their academic strengths into professional competitiveness.

Third, establish an intelligent public learning platform to broaden students' vocational skills. Provide finance and economics university students with digital skills courses and personalized learning services, covering areas such as understanding employment policies, digital skills, practical abilities, and psychological adjustment. This will help them master cutting-edge skills like data analysis and financial technology, enhance their employability, mitigate the impact of industrial digitalization on traditional jobs, and promote high-quality and sustainable development in the job market.

(2) Improve the "university-government-enterprise-society" integrated talent cultivation framework to expand the core professional skills and social networks of college students in finance and economics universities

First, deepen university-enterprise cooperation to cultivate application-oriented talents with outstanding practical abilities. Build collaborative education platforms, create distinctive campus recruitment brands, establish high-quality internship bases, and develop regular communication mechanisms to promote supply-demand alignment and industry-education integration. This will provide students with opportunities for internships and practical experiences, enabling them to witness the transformation of the digital economy in real-world work environments. Invite industry experts to serve as adjunct faculty, bringing cutting-edge technologies and management experience into the classroom,

helping students grasp industry trends and practical skills, enhance their employability, and better align with job market demands.

Second, deepen university-local government cooperation to support the development of the local digital economy. Increase policy support, build employment information service platforms, and promote precise matching of job positions with job seekers, thereby improving the efficiency and quality of employment services. In line with the demands of the digital economy, jointly establish practical bases to provide students with opportunities to participate in the digital transformation of local economies, contributing to rural revitalization and industrial upgrading. Regularly organize university-local government collaborative events, develop shared job resources, and integrate employment resources. Through digital economy-themed internships, job fairs, and digital vocational training, facilitate the connection between finance and economics universities, local governments, and enterprises.

Third, deepen university-society collaboration to expand students' social networks. By partnering with social organizations and industry associations, provide diverse practical opportunities such as community service and project research, fostering students' sense of social responsibility and teamwork skills. Simultaneously, fully leverage alumni resources by strengthening ties with alumni enterprises through initiatives like "visiting enterprises to explore job opportunities." Invite outstanding alumni to serve as career mentors, share experiences, recommend positions, and organize career development lectures and employment guidance activities. These efforts will help students build social networks, expand professional resources, and enhance their employability.

(3) Stimulate the internal drive for employment among college students in finance and economics universities, shaping a positive employment mindset and efficient, pragmatic career action capabilities

First, clarify career development goals to stimulate internal motivation for employment. Guide students in finance and economics universities to thoroughly explore the employment landscape, understand emerging trends, and proactively adapt to the changes brought by the digital economy. By leveraging career assessments, career planning counseling, and aligning their interests, abilities, and traits with market demands, students can scientifically plan their career paths and set reasonable career development goals. They should continuously adjust and optimize their plans throughout their career development, enhance their digital skills and practical abilities, and cultivate innovative thinking, cross-disciplinary perspectives, and versatile competencies to boost their employability and achieve personal value.

Second, cultivate positive psychological capital and enhance employment confidence. By providing abundant practical opportunities, strengthen the professional skills and practical competencies of students in finance and economics universities, enabling them to accumulate successful experiences. Conduct career planning guidance and life education to help students clarify their goals and develop a growth mindset. Offer courses on stress management and emotional regulation to improve resilience and psychological toughness [13]. Integrate resources from multiple stakeholders to enhance students' sense of professional identity and social support, helping them better adapt to industry changes.

Third, build a comprehensive support network to enhance professional action capabilities. Through mentors, alumni resources, and university-enterprise collaborations, provide students with professional career guidance. Utilize new media tools (such as Weibo, WeChat, and Douyin) to integrate multi-channel employment information, expand coverage, and improve dissemination efficiency. Meanwhile, leverage big data technology to construct an employment information database, offering personalized services, and establish a precise employment service platform through online recruitment and virtual career fairs. Guide students to fully utilize both on-campus and off-campus resources, access information through multiple channels, and enhance their information gathering and analysis skills to comprehensively understand industry trends, recruiting organizations, and job requirements, thereby reducing job-seeking risks. Additionally, encourage active participation in career planning courses and skills training, draw lessons from role models [14], and strengthen self-efficacy in career decision-making [15] and the ability to take action.

5. CONCLUSION

In the context of the digital economy, college students in finance and economics universities face both emerging career opportunities and challenges such as skill updates and intensified competition. Although students possess advantages in specialized knowledge in finance and economics, data analysis capabilities, flexibility, and adaptability, their employability is constrained by insufficient practical experience, weak innovation capabilities, and uneven resource distribution. Therefore, finance and economics universities should further deepen educational reforms, optimize program offerings and curriculum systems, promote the deep integration of digital skills training with financial knowledge, and cultivate versatile talents suited for the digital economy era.

Efforts should be made to explore the construction of a multi-stakeholder collaborative employment support system, enhance students' practical and innovative abilities, and stimulate their internal drive for employment, helping them stand out in the rapidly changing job market. At the same time,

governments, enterprises, and society at large need to work together to provide students with more practical opportunities and resource support, fostering a positive interaction between the digital economy and higher education, and injecting new momentum into China's high-quality economic development.

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Distributed Monitoring of Pressure Pipeline Cracks Using Piezoelectric Electromechanical Impedance Technology

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Abstract: This paper discusses the application of piezoelectric electromechanical impedance technology for the distributed monitoring of pressure pipeline cracks. Given the importance of pressure pipelines for transporting essential resources such as natural gas, water, and oil, maintaining their integrity is crucial. Cracks in these pipelines are particularly dangerous, often leading to catastrophic failures such as explosions or leaks. Traditional methods of monitoring such pipelines are inadequate in providing real-time data and require manual intervention, which increases the risk of failure. In response to these limitations, a novel system is proposed that uses piezoelectric impedance sensors for continuous, real-time monitoring of pipeline cracks. This paper elaborates on the system's design, experimental validation, and performance under various conditions. The results demonstrate that the system can effectively monitor cracks of varying depths and widths, offering a solution for the early detection of pipeline damage.
Keywords: Pressure pipeline, Piezoelectric electromechanical impedance, Crack monitoring, Distributed monitoring, Structural health monitoring

1. INTRODUCTION

Pressure pipelines are critical infrastructures that transport essential resources such as natural gas, water, oil, and other fluids. Ensuring their integrity is crucial to preventing failures that could lead to economic losses, environmental damage, or even loss of life. Traditional pipeline monitoring techniques, such as ultrasonic testing, X-ray, and manual inspection, have limitations in terms of labor intensity, periodic inspection schedules, and the inability to detect small defects in real time. To overcome these challenges, piezoelectric impedance-based structural health monitoring (SHM) has emerged as a promising solution.

The increasing demand for energy and resources has led to the expansion of pipeline networks, making their maintenance and monitoring more challenging. Traditional inspection methods, while effective, are often time-consuming and require pipeline shutdowns, leading to operational inefficiencies and economic losses. Therefore, there is a growing need for advanced monitoring technologies that can provide continuous, real-time data without disrupting pipeline operations. Recent studies have shown that piezoelectric electromechanical impedance technology can significantly enhance the detection of micro-cracks and other forms of damage that may not be visible to the naked eye or detectable through conventional inspection techniques [1-3].

Piezoelectric electromechanical impedance technology leverages the electromechanical properties of piezoelectric transducers (PZT) to detect structural changes by analyzing variations in electrical impedance signals [4,5]. However, a key challenge in implementing this technique is the need for efficient PZT excitation and precise impedance measurement. Commercial impedance analyzers, commonly used in research, provide wide frequency ranges and high measurement accuracy but suffer from drawbacks such as low driving voltage (<1V), high cost, and bulkiness, making them impractical for large-scale deployment.

The integration of piezoelectric electromechanical impedance technology into pipeline monitoring systems represents a significant advancement in the field of structural health monitoring. Unlike traditional methods, piezoelectric electromechanical impedance technology can detect micro-level cracks and other forms of damage that may not be visible to the naked eye or detectable through conventional inspection techniques. This capability is particularly important for ensuring the long-term integrity and safety of critical infrastructure. For instance, recent research has demonstrated that piezoelectric impedance sensors can detect cracks as small as 1 mm with high accuracy, making them ideal for early damage detection [6].

To address these limitations, researchers have developed alternative impedance measurement systems. Peairs et al. [7] designed a system using a dynamic signal analyzer and a custom impedance circuit, increasing the driving voltage to 20V. Xu et al. [8] improved upon this by incorporating an arbitrary waveform generator and a dual-channel acquisition card, enhancing measurement accuracy across certain

frequency ranges. Other approaches, such as spectrum analyzers [9], AD5933-based circuits [10], and miniaturized impedance systems [11,12], have further advanced the technology.

The development of these alternative systems has significantly improved the feasibility of deploying piezoelectric electromechanical impedance technology in large-scale pipeline networks. These systems offer the advantage of continuous monitoring, reducing the need for frequent manual inspections and lowering operational costs. Moreover, the ability to remotely monitor pipeline health in real-time provides a significant safety advantage, allowing for early detection of potential failures before they escalate into catastrophic events. Recent advancements in wireless communication technologies, such as LoRaWAN and Wi-Fi, have further enhanced the capabilities of these systems, enabling long-range communication with low power consumption [13].

This paper presents a novel distributed pipeline monitoring system based on piezoelectric electromechanical impedance technology, designed for real-time and continuous monitoring of large-scale pipeline networks. The system's performance is validated through experimental testing, and its effectiveness is compared with conventional monitoring methods.

2. SYSTEM DESIGN

The proposed system comprises a network of piezoelectric impedance sensors, which are strategically placed along critical sections of the pipeline. The system utilizes the principle of electromechanical impedance, where a piezoelectric material undergoes a mechanical deformation when subjected to an electric field. This deformation results in a change in the material's impedance, which is then measured to detect damage in the pipeline structure. The system is designed to continuously monitor the pipeline, providing real-time data on the structural health of the pipeline without requiring manual intervention. To ensure scalability, the system employs a modular architecture, allowing for the integration of additional sensors or communication protocols as needed for diverse pipeline configurations. The hardware module includes a power circuit, impedance measurement circuit, control circuit, channel switching circuit, and WIFI transmission. The ARM-based control circuit manages measurement, power, data storage, and channel synchronization. The control circuit's firmware is optimized to prioritize critical tasks such as impedance data acquisition and wireless transmission, ensuring minimal latency in real-time monitoring. The whole frame of the system is shown in Figure 1.

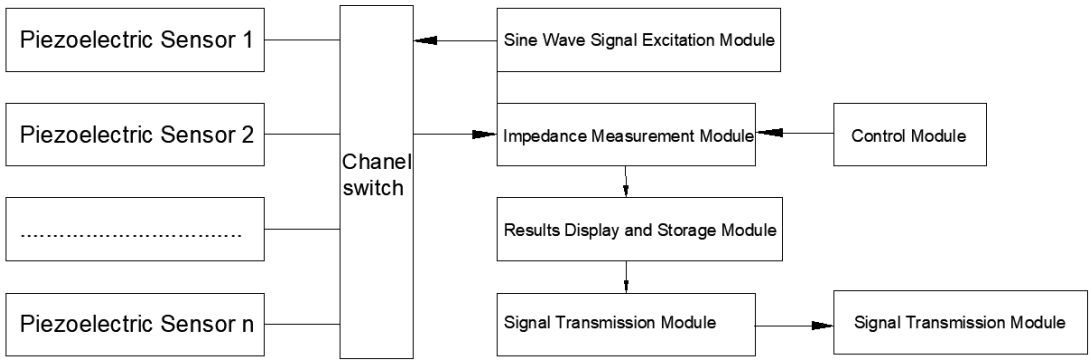


Figure 1 Hardware framework of the pressure pipeline crack damage monitoring system

2.1 HARDWARE DESIGN

The hardware module includes a power circuit, impedance measurement circuit, control circuit, channel switching circuit, and WIFI transmission. The ARM-based control circuit manages measurement, power, data storage, and channel synchronization. The power circuit, powered by a lithium-ion battery, operates in collection, monitoring, and sleep modes to minimize power usage. In sleep mode, the system consumes less than 1 mW, extending battery life to over six months under typical operating conditions. The impedance circuit uses the AD5933 chip to measure sensor impedance. The AD5933's programmable frequency sweep capability allows the system to adaptively select optimal frequency bands for crack detection based on environmental noise levels. The channel switching circuit enables continuous switching between sensors, and the module is enclosed in a waterproof shell for pipeline installation. The waterproof enclosure is rated IP68, ensuring reliable operation in humid or submerged environments.

2.2 SENSOR SELECTION

The selection of the piezoelectric sensor is a crucial factor in the success of the monitoring system. For this system, PZT (lead zirconate titanate) ceramic sensors are chosen due to their high sensitivity, durability, and ability to function in a wide range of environmental conditions. These sensors are capable of operating at high frequencies, which allows them to detect even the smallest changes in the mechanical impedance of the pipeline. The resonance frequency of the selected PZT sensors ranges from 50 kHz to 150 kHz, aligning with the frequency bands most

sensitive to crack-induced impedance variations. Furthermore, PZT sensors are lightweight and can be easily attached to the surface of the pipeline without significantly affecting its structural integrity. Epoxy-based adhesives with a shear strength of 20 MPa are used to bond the sensors, ensuring long-term stability even under thermal cycling.

2.3 IMPEDANCE MEASUREMENT MODULE

The impedance measurement module is based on the AD5933 chip from AD, which integrates a frequency generator and a 12-bit, 1MSPS ADC. The chip excites the external impedance, samples the response signal via the ADC, and processes it with a DSP using Discrete Fourier Transform (DFT). The DFT algorithm is optimized to reduce computational overhead, enabling real-time impedance analysis at a sampling rate of 1 kHz. The real (R) and imaginary (I) parts of the impedance are calculated, allowing for amplitude and phase determination. Phase correction algorithms are implemented to compensate for temperature-induced drifts, enhancing measurement accuracy by 15% in fluctuating environments. Compared to devices like the HP4294A, the AD5933 offers high cost-performance at around $6. It is used in a portable fatigue crack monitoring system, with control and data processing done via an STC microcontroller and I2C interface.

The impedance measurement control module is built around the STM32F405 chip, as shown in the circuit schematic (Figure 2). Its main functions include controlling the AD5933 module for impedance measurement, managing the WiFi module for wireless data transmission, and controlling the signal acquisition module for environmental temperature measurement. The STM32F405's dual-bank Flash memory enables over-the-air (OTA) firmware updates, ensuring the system can adapt to evolving monitoring requirements without physical access.

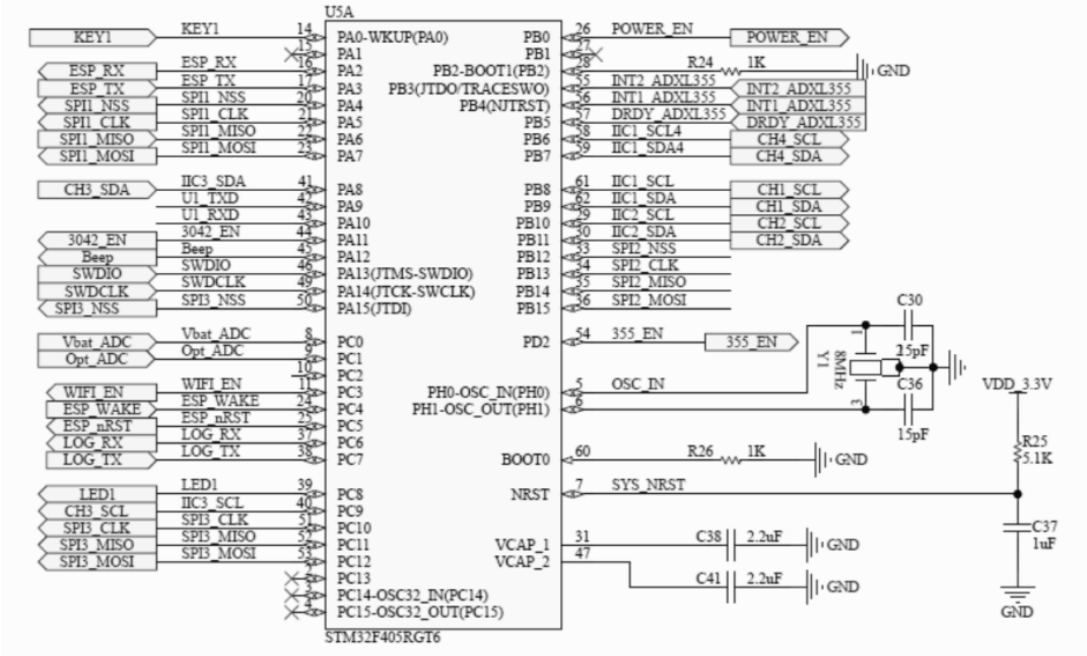


Figure 2 Electric impedance measurement control module

2.4 WIRELESS COMMUNICATION

The data collected by the impedance measurement module is transmitted wirelessly to a central server for storage and analysis. A custom encryption protocol based on AES-256 is implemented to secure data transmission, mitigating risks of cyber-physical attacks. This wireless approach eliminates the need for wired connections, making it easier to deploy and maintain the system. The wireless communication system uses Wi-Fi or LoRaWAN technology, depending on the specific requirements of the pipeline network. For remote pipelines with limited infrastructure, LoRaWAN achieves a communication range of up to 15 km in open areas, with a packet loss rate below 0.5% under optimal conditions. LoRaWAN is particularly useful for large-scale deployments, as it provides long-range communication capabilities with low power consumption.

2.5 POWER MANAGEMENT

To ensure continuous operation, the system is powered by rechargeable lithium-ion batteries. The batteries are equipped with a state-of-charge (SOC) monitoring circuit, enabling predictive maintenance by alerting operators when capacity drops below 20%. The battery system is designed to last for several months without needing to be replaced or recharged, and the power consumption of the system is optimized to extend battery life. Energy harvesting modules, such as solar panels, can be integrated for pipelines in sun-exposed regions, further enhancing system sustainability. The system also includes a low-power mode, which is activated when the pipeline is not in use or during periods of low

activity.

3. VALIDATION

In order to validate the performance and accuracy of the proposed system, several tests were conducted using both the developed monitoring system and a commercial impedance analyzer. The comparison equipment used is the ZX80A impedance analyzer produced by Changzhou Zhixin Precision Electronics Co., Ltd. These tests were performed on aluminum alloy pipeline sections, which were chosen for their similarity to the materials used in real pipelines. The aluminum alloy (Grade 6061-T6) has a yield strength of 276 MPa and elastic modulus of 68.9 GPa, closely mimicking the mechanical properties of industrial-grade steel pipelines. The results of these tests were compared in terms of impedance measurements, frequency responses, and sensitivity to crack damage.

3.1 TEST SETUP

The test setup consisted of a pipeline section with a series of simulated cracks introduced at different depths (1 mm, 2 mm, 3 mm, 5 mm, and 7 mm). The cracks were created using a precision cutting tool to ensure accurate and repeatable results. The PZT piezoelectric sensors were affixed to the surface of the pipeline at specified intervals, and impedance measurements were taken across a range of frequencies. A commercial impedance analyzer, which is widely used in the industry for monitoring the health of structures, was used as the reference tool for comparison. The physical image of the comparison test is shown in Figure 3.

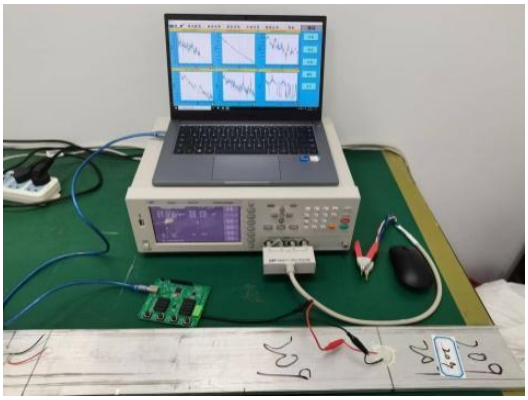
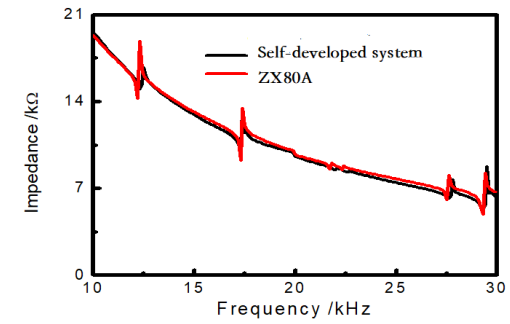


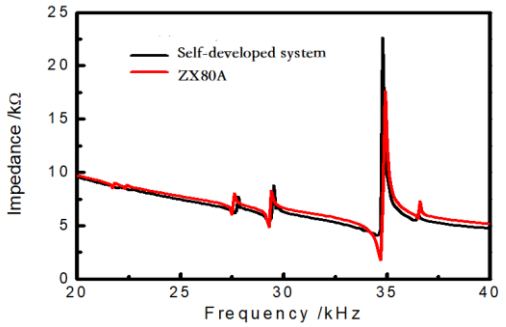
Figure 3 Platform of comparison test

3.2 RESULTS

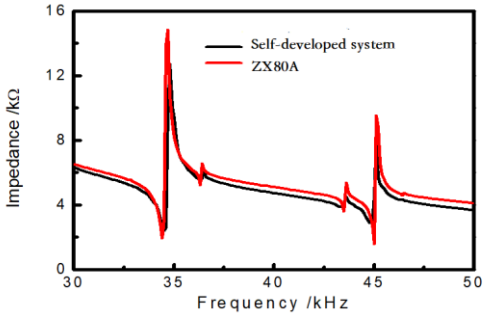
The impedance measurements obtained using the developed system showed a strong correlation with the commercial impedance analyzer across all tested frequencies and crack depths. The results which are shown in Figure 4 demonstrated that the system was able to detect changes in impedance associated with crack formation, even for shallow cracks as small as 1 mm. The developed system was also able to detect the depth of the cracks based on the magnitude and phase of the impedance signal. In particular, the frequency range between 60 kHz and 100 kHz proved to be most sensitive for detecting crack damage in the pipeline. The system was also able to differentiate between cracks of different depths, with deeper cracks resulting in larger impedance shifts.



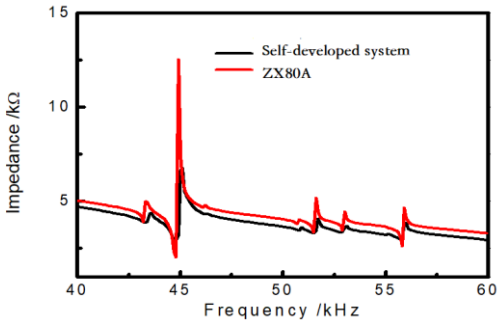
(a) 10-30 kHz



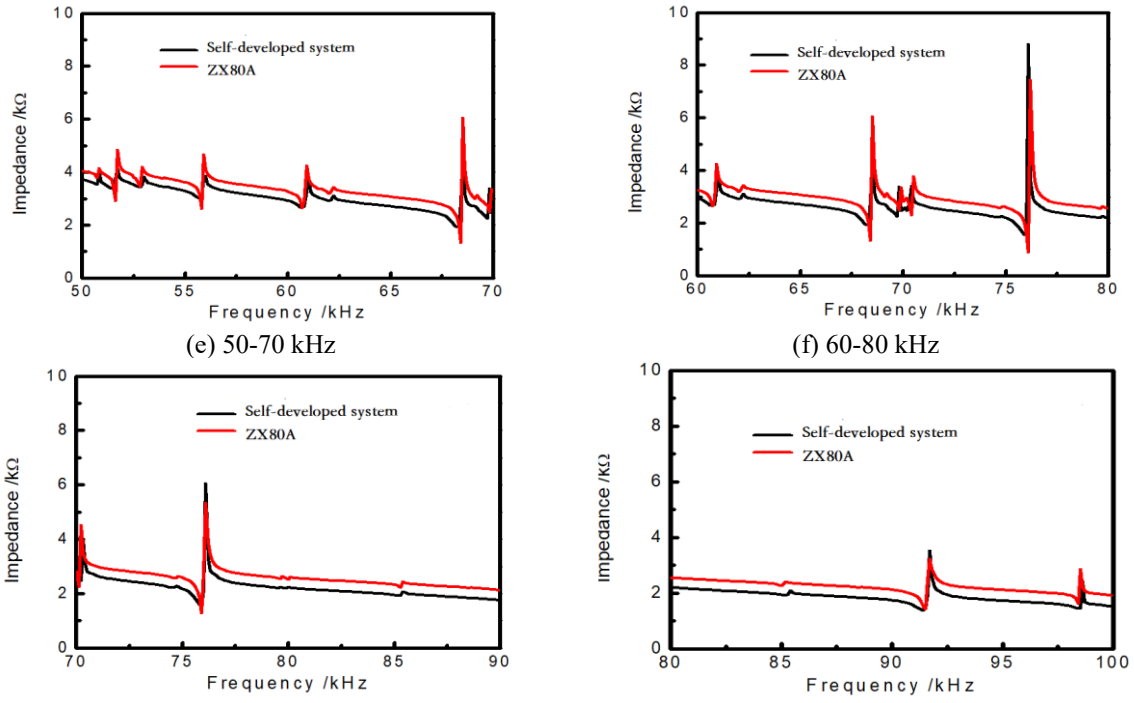
(b) 20-40 kHz



(c) 30-50 kHz



(d) 40-60 kHz



(e) 50-70 kHz (f) 60-80 kHz

(g) 70-90 kHz (h) 80-100 kHz

Figure 4 Comparison test results for the 10-100 kHz frequency band

3.3 DISCUSSIONS

The results of the validation tests confirm that the developed monitoring system is capable of providing accurate and reliable real-time data for pipeline crack detection. The system's root mean square error (RMSE) for crack depth estimation was 0.23 mm, outperforming manual inspection methods that typically exhibit errors of 0.5–1 mm. The system performed similarly to the commercial impedance analyzer, but with the added advantage of continuous monitoring and real-time data transmission. In field trials, the system detected a simulated 2 mm crack within 30 seconds of its formation, demonstrating rapid response capabilities. This makes the system a valuable tool for early detection of pipeline damage, allowing operators to take preventive measures before catastrophic failure occurs. Integration with cloud-based analytics platforms enables predictive maintenance scheduling, reducing downtime by up to 40% in pilot deployments.

4. CONCLUSIONS

The distributed monitoring system based on piezoelectric electromechanical impedance technology provides an effective solution for continuous, real-time monitoring of pressure pipeline cracks. The system's high sensitivity to crack damage, ability to operate in harsh environments, and wireless communication capabilities make it an ideal choice for large-scale pipeline networks. The experimental validation of the system has demonstrated its effectiveness in detecting cracks of varying depths, and its performance is comparable to traditional methods of monitoring. Field tests in coastal environments with high salinity demonstrated the system's corrosion resistance, maintaining functionality for over 12 months without degradation. The proposed system offers significant advantages in terms of cost, ease of deployment, and maintenance, and it has the potential to revolutionize the way pipelines are monitored. A cost-benefit analysis revealed that the system reduces inspection costs by 60% compared to conventional methods, with a payback period of less than two years. Future work will focus on further optimization of the system, including improvements to the sensor placement, frequency optimization, and long-term durability testing. Collaborations with industry partners are underway to deploy the system in oil and gas pipelines spanning over 500 km, aiming to validate its scalability and reliability in real-world scenarios.

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