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Mapping Technological Trajectories as Patent Citation Networks: Taking the Aero-Engine Industry as an Example

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***Abstract*--Technological evolution is considered to be taking place along requirements and selective patterns change, shaped jointly by technological and scientific principles, and economic and other societal factors. Historical, descriptive analysis is often used to analyze trajectory. This paper uses patent bibliometric analysis and patent network analysis to monitor technological trajectories in the field of aero-engine. In this way we can easily recognize genuine paradigmatic changes compared to more regular changes in trajectory. Our aim is to identify when such changes took place in different generations of technological advances this industry has seen. Combined with the empirical research of aero-engine industry, we not only explain the dynamic identification method of technological trajectory, but also describe the process of technology changes in detail. These results first reveal different aspects of patenting activities in aero-engine field. Then, patent network analysis indicates the developmental tendency of worldwide aero-engine production based on different technology backgrounds. Furthermore, key technologies can be identified which provide the opportunity to improve the efficacy in the path of main-stream technology for enterprises.**

I. INTRODUCTION

Aircraft engine is the component of the propulsion system as the heart of the aircraft that generates mechanical power. It is an important determinant of aircraft performance, which indicates the level of a country's research, development and manufacturing ability of mechanical power. Due to extremely difficult nature of technology and the demands for composite materials and complex manufacturing process, the development of aircraft engine has been commonly viewed as the symbol of a country's advancement in science and technology, industry, economy and national defense. Positioned at the top of industry chain, the development of aircraft engine can boost the breakthrough of key technologies in large groups, significantly enhancing the aviation industrial foundation and technical capacity, promoting scientific and technological progress and forming an increasingly powerful competitive advantage. Therefore, the retrieval and analysis of the patents information encompassing the field of aircraft engine can reveal the rules of development and evolution, which make important and practically significant step in raising the starting point of indigenous innovation and avoiding industrial low-level and redundant research and development.

Technology trajectory refers to a single branch in the evolution of a technological design of a product or service, with nodes representing separate designs [1]. Dosi [2] proposed the concepts of technological paradigm and technological trajectory in 1982, and defined the technological trajectory as the paradigm-dependent technological progress path compromised between economy and technology [3], [4]. Since 1990s, many scholars, including Dosi, have recognized the limitation of the definition of technological trajectory. Mark J[5], [6]and some other scholars figured out that the nature of the technological trajectory actually is the feasible path of technical innovation according to the specific technological pattern bound by both economic and technical variables. The technological trajectory often demonstrates the possible direction of the technology development, and the outer frontiers are often determined by the technological paradigm itself. Dierickx [7] and other scholars defined the technological trajectory as the dependent path in pursuit of the development of certain technology.

In continuous research on technological trajectory, many scholars have launched the study from the aspect of patent citation. Hummon [8] and other scholars have put forward three generating methods of main paths, including depth first search, exhaustive search, and traversal counts. Dosi [9] creatively proposed that the technological trajectory may be derived from the citation path in patent citation network. To identify the technological trajectory with connectivity in patent citation network, Mina [10] and some other scholars figured out that the patent connectivity analysis in the patent citation network may form the continuous patent development path, which improves the catch-up technology. With combination of methods from Hummon and patent citation network, the technological trajectory of fuel cell [11], ethernet technology [12] and the telecommunication [13] have been found respectively, which demonstrated the effectiveness of this method [14].In current research, the citation chain can be shaped by Hummon's method to reflect the direction, process, characteristic and rules of patent information. The citation relationships and principles can be indicated to reveal improving direction and development tendency in certain industry or in certain technology [15]. Moreover, Mina *et al.*[16], Verspagen[17], Fontana[18], Barbera *et al.*[19] addresses the challenge of validation concerns i.e. empirical operationalization and the availability of comparable data by defining technological trajectories in terms of knowledge flows within a patent citation network. Jaffe and Trajtenberg [20] suppose that the nodes of the patents network and citations indicate the knowledge flows between them.

Studying all these literatures published by different scholars, we can know that the existence of technological trajectory and its contributions to the research of the technology development have been commonly accepted.

However, some scholars have already carried out dynamic properties research of technological trajectory. For example, Upham and Small [21], Shibata *et al.* [22], Small[23], Chen *et al.*[24] have tended to draw into the dynamics through employing temporal information to track which technology of one particular time window has evolved into which technology in the next time window, it allows researchers to form what are referred to as science or technology trajectories[25].Trappey *et al.* [26] points out that analyzing the dynamic change of technology trajectories would help enterprises to realize technical predictions and make technical decisions keeping up to date with technological trends.

However, in the above literatures, the technology life cycle has not been considered in the process of the technological evolution, and there is no detailed description about how to divide the technology trajectory into different stages. Therefore, the identification of the stages in the dynamic evolution of technological trajectory and the determination of its future trend is still the research questions worthy of deep exploration. Above all, according to the technology life cycle, this study intends to identify and map the technological trajectory about aircraft engine based on the aircraft engine related patents and the corresponding citation networks. In this way, the basic process of technological trajectory mapping related to aircraft engine and its realizing procedures could be explored, to develop the technicians' understanding about the key technology of aircraft engine from the aspects of patented technology. Moreover, the study could technically support and improve the research and development of the aircraft engine, and provide references to structure the proprietary intellectual property right system.

II. METHODOLOGY AND DATA COLLECTION

The technological trajectory is shaped by the technology transitivity, and the patent citation network is just the reflection of technology transitivity. Jaffe and Trajtenberg [27] interpreted in details that a reference to a previous patent indicates that the knowledge in the latter patent was in some way useful for developing the new knowledge described in the citing patent. In the patent citation network, the citation, distribution, restructure of technology and other dynamic activities can indicate the shift of current technology and generation of new technology, therefore, it is sound to explore the evolution of technology trajectory by patent citation network. Just as Bart Verspagen pointed that (in Refs.xxv) citing patents may themselves become cited in the future, so that we will be able to"map chains"of ideas as they develop over time.

A. The principle of patent citation network

Individual patent can be regard as a piece of knowledge, or an innovation idea and the presence of one citation to patent A in patent B as an indication that patent B builds upon patent A or B source knowledge from multiple previous patents A. Then, fig.1 is taken as an example to explain a simple dynamic flow of technology in the process of patent citation.

Fig.1 described a simple knowledge activity in the process of patent citation. Nodes of p1-p6 represent 6 singular patents. The arrow points to the direction of knowledge moving towards. The citing processes, including p1→patent p2, p3, p5, patent p2 →patent p3, p4, p5, patent p3 →patent p5, p6, can be viewed clearly. Knowledge from Patent p1 move forward layer by layer, and they can directly reach to the patent nodes of p2, p3, p5 or indirectly move to nodes of p4, p6. In the knowledge moving process, the knowledge itself hardly keeps constant. For instance, (p2+p3+p4+p5) →p6 actually shows the knowledge restructure process. p3, p4, p5, p6 have gradually distributed the knowledge in patent p1, and the knowledge integration or restructure may emerge when the accumulation arrives to certain degree. The process of p1→p6 does not happen suddenly, but gradually moves forward layer by layer of the other nodes. P3 and p5 oversteps its preceding citing patent, then the effects can be showed as p3> (p1+p2), p5> (p1+p2+p3). P6 ought to continue moving forward based on the p3 and p1, then the knowledge qualitative change will finally happen. In this process, the brand new knowledge unit different from p1 might generate to realize the knowledge development and restructure. From above processes, patents of p1- p5 can be recognized as the innovation cluster in same technological paradigm, which present the extension of the technological trajectory. Patent p6 is affected by new technological paradigm, which presents the leap of technological trajectory.

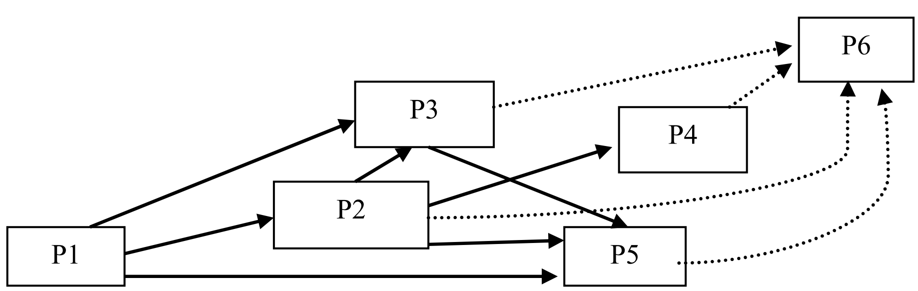

Fig.1.The Knowledge Activities in Patent Citation [28]

From the analysis of above principles, in the complicated citation network, we can abstract the representative technological flow path, which is composed of a series of continuous patent citation. Through the simplification of this patent citation network, the required technology trajectory can be attained. The detailed simplification algorithms are described as follows.

B. Fundamental algorithm

To abstract the representative technological trajectory in citation network, the core is the identification of these key codes. Then we can simplify the complex network by cutting out those less relative codes. Hummon and Doreian [29] suggested that the importance of each link is determined by the link's traversal weight, which is measured by calculating the number of times a citation link has been traversed from a set of staring nodes to another set of ending nodes [30], [31].Von Wartburg [32] figured out that determining whether the nodes are the key nodes or not depends on the importance of individual node and its connectivity to the whole structure of the network. According to this consideration, the Search Path Link Code, abbreviated as SPLC, is used as an index to measure the core technology trajectory in the network.

In the network there are four main types of patents: starting patent, ending patent, intermediate patent and isolated patent. Starting patent refers to that patent only with citing patent but no cited patent; ending patent is only with cited patent but no citing patent; intermediate patent is with both cited patent and citing patent; isolated patent is neither with cited patent nor with citing patent. When SPLC is used, first it needs to analyze all paths from starting patents to ending patents, and then calculate the number of occurrences of directed edges in all paths which is the values of SPLC. The SPLC value of isolated patent is 0. Finally, the path with the largest SPLC is selected as technological trajectory. Fig 2 is shown to simulate the way of computing.

In the Figure 2, the nodes "O", represents the patents, the directed edges "→" represent the citation relationship between the citing patent and the cited patent. For example, directed edge A→C shows patent A is cited by patent C, which directly reflects that patent C is the further development of patent A and technology flows from the cited patent A to the citing patent C while there is no technology flow among isolated patents. In Figure 2, there are 15 patents, including 4 starting patents, 4 ending patents, 2 isolated patents, 5 intermediate patents, which form 14 connected paths. Take patent A as starting patent, there are 4 connected paths, including A→C→E→F, A→C→E→H→I, A→C→E→H→J→L→M, A→C→E→H→J→L→N; Take patent B as starting patent, there are 6 connected paths, including B→C→E→F, B→C→E→H→I, B→C→E→H→J→L→M, B→C→E→H→J→L→N, B→J→L→M, B→J→L→N. Take patent D as starting patent, there are 4 connected paths, including D→E→H→J→L→M, D→E→H→J→L→N, D→E→F, D→E→H→I. The SPLC line A→C is 4, which means there are 4 links in total between A and C in all the paths of the whole network, including A→C→E→F, A→C→E→H→I, A→C→E→H→J→L→M, A→C→E→H→J→L→N. For another example, SPLC of line C→E equals 8, which shows the 8 paths including A→C→E→F, A→C→E→H→I, A→C→E→H→J→L→M, A→C→E→H→J→L→N, B→C→E→F, B→C→E→H→I, B→C→E→H→J→L→M, B→C→E→H→J→L→N. As measured above, the SPLC of every edge can be calculated in this way. Then, the total value of SPLC can be measured, and the path with largest SPLC may be viewed as the technology trajectory. For example, the path A→C→E→H→J→L→M, A→C→E→H→J→L→N, B→C→E→H→J→L→M, B→C→E→H→J→L→N is selected with the largest component in the network of main paths with SPLC value of 39 shown in Figure 3. The technological trajectory has been mapped with starting patent at A and B and with ending patent at M and N, which pass through C, E, H, J, and L.

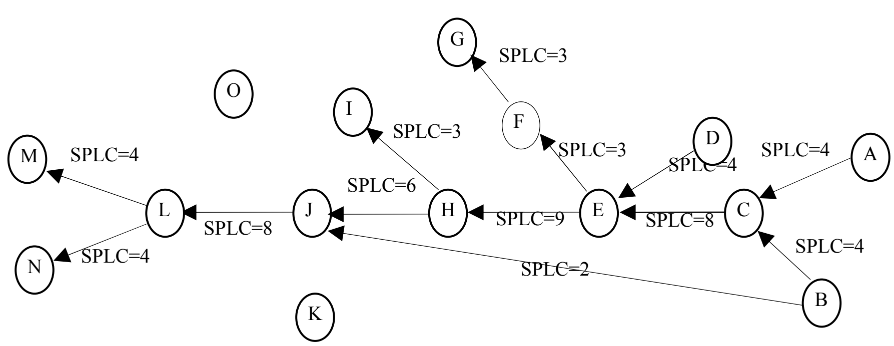

Fig.2. Weight Measuring of Paths and Node Pairs

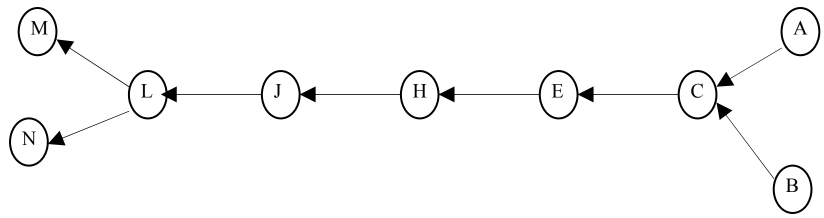

Fig.3.The Technological Trajectory Scheme after Identification

C. Data Collection and Processing

The process of aircraft engine-related patent data analysis is as follows.

1) Determine the patent documents. The patent searching measures have been confirmed by discussion with experts. The Thomson Innovation patent database is used to search the patents. The patents applied in different countries may belong to the same patent family, which refers to the same technology being protected in different countries. To avoid the duplications, the patent data need to be processed. Because most of the patents are usually applied in America, the American patents are typically representative. Furthermore, the American patents are more detailed in citation information compared with those of other countries. Therefore, the patents applied in America are decided to be studied as the research samples.

2) The downloaded data are then processed by software VBA as the processing tool. The unqualified data are deleted, which have common problems like irregular format or lacking analytical terms.

3) Build up the patent citation matrix. The patents in the Thomson Reuters, which is an online patent analysis system, are often high in objectivity and authority. By patent data derivation in the technology progress process, the patent citation pairs are obtained, which are used to structure the patent citation matrix. These data are exported as the excel document and analyzed as the original data.

4) Derive the technological trajectory. The software, Ucinet and Netdraw, are applied as the analyzing tools of technological trajectory, which can systematically analyze the connectivity of developing paths about the interior technology. Software Pajek is used to map the technological trajectory. Then, considering the patent application time, the patents are re-arranged in order of patent time.

5) Divide the stages of technology development. According to changing patent numbers over the years, the development trends in technology and research trends in investment are visualized. In specific technology field, these trends often have periodic features, which indicate that the technology has different development state in different stages. From the analysis of variables with changing time, developing speed and trend can be reflected to some degree. Therefore, the stages can be divided through the changing patent number over the years.

This study takes title/abstract/claim = (aviation motor, aviation engine, aero-motor, aero motor, aero-engine, aero engine, aeroengine, aerial motor, aerial engine, aircraft engine) as searching words, data source= (United States Patent and Trademark Office<USPTO>) as database and type= (granted patent) as optimization. Through processing these searched patent data, 4956 terms of patent data in total have been finally collected. In order of application years, Figure 5 is profiled to show how the aircraft engine patent number changes. From this profile, the aircraft engine development process in different stages can be displayed.

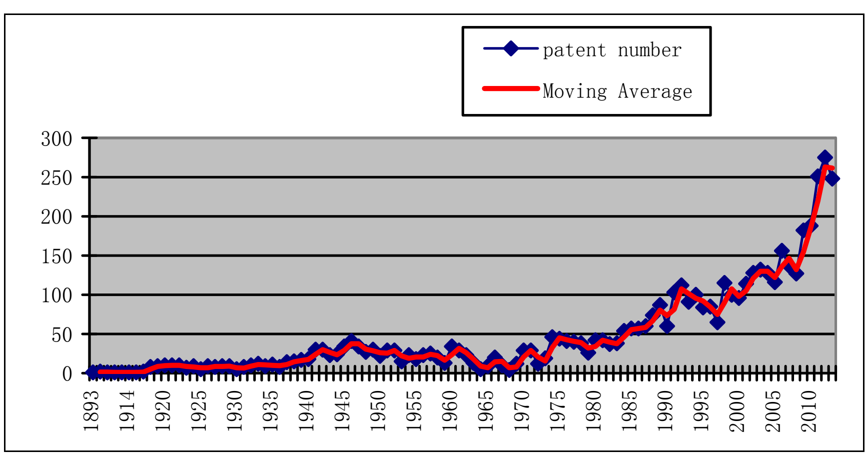

Fig.4.The Aircraft Engine Patent Numbers in Order of Application Years

In the Figure 4, the shape of annual aero-engine patent number profile is analogous to the curve of product life cycle which was first put forward by Vernon. Ernst [33] figured out that the activities of patents present uncertain forms in different stages of the development life cycle. He also figured out when the vertical axis shows the number of application of patent and the horizontal axis shows timeline, the curve of S appears and it can display the evolution of technology life cycle which can also be called technology diffusion or the process of technology evolution. Popper [34] pointed out that comprehending technology life cycle is more important than product life cycle for technical products. Arthur D Little[35]clearly defined the technology life cycle, and other scholars, such as Harvey[36], Roussel[37], Betz Frederick [38], Khalil[39] have investigated the stage partition of technology life cycle.

According to the above theories of technology life cycle, if one needs to inquire how well one technology has developed, it is essential to clarify in which life cycle stage the technology is in. The patent intelligence analysis is the most effective way to decide the stages of technology life cycle. Therefore, the stages of the aircraft engine technology evolution are divided based on above analysis in this study

From the curve in Figure 4, the process is divided into three stages from 1893 to 2013. ①The years from 1893 to 1970s is the sprout period. The aircraft engine technology has just started, with very small and similar patent numbers in each years of the stage. The yearly application number is about 20. ②The years from 1970s to 1990s is the growth period. The yearly aircraft engine patent numbers have substantially increased with linear changes in yearly distribution. The yearly application number is no more than 100 but higher than before.③The year from 2000 to 2013 is the diffusion period. The yearly patent numbers burst with index changes in yearly distribution, which indicates the increasing interest in development of aircraft engine and substantial technology achievements.

For the three stages described above, the technology of aircraft is in its infancy and the patent numbers is little in the sprout period. With the technology of aircraft engine growing to maturity and with the market competition intensifying, the patent applications increase yearly. Especially at the end of 20th century, the flows of technology and products moving across the world speed up along with R&D globalization and innovation of internationalization increasing rapidly, which step up technological innovation in the aircraft engine. While the series of new type turbine engines have came into the market, the yearly patent application number had reached the top. The characteristics of the stages in different development of aircraft engine will be detailed in part III.

III. THE PATENT CITATION NETWORK MAPPED AND TECHNOLOGICAL TRAJECTORY IDENTIFIED

A. The patent citation network

4596 patents of aero-engine have been researched and processed, and 68920 citation relations are visualized on aimed patents and reference. After importing it into Pajek software, the largest component in the network of main paths is shown in Fig5.

Technology trajectory consists of the network of patents citation. We calculate the SPLC of each node in fig5 with the help of the Pajek software according to the way that we have discussed in the method, deleted some secondary nodes, and then get the main path of aero-engine. It can be seen in figure 6.

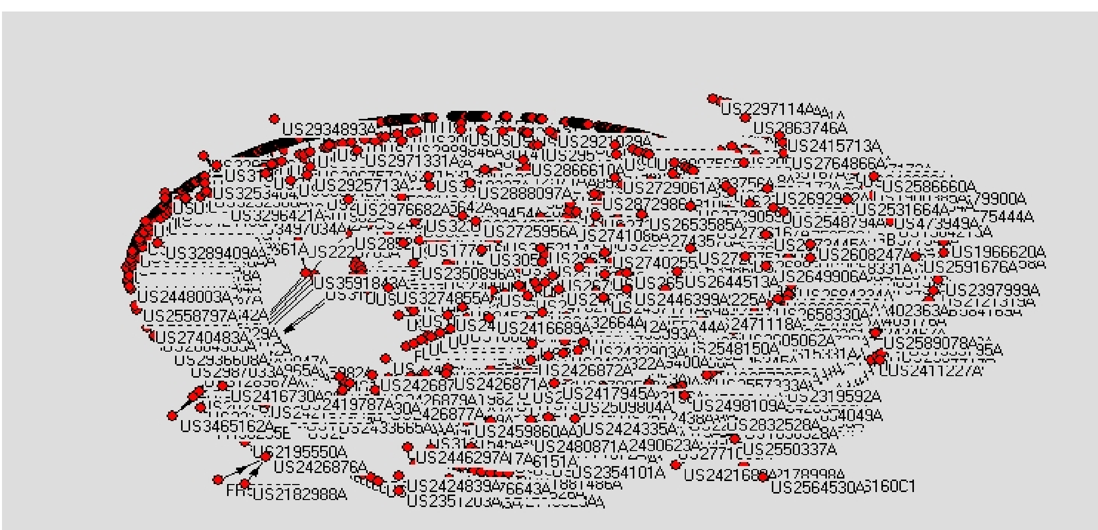

Fig.5.The Largest Component in The Network of Main Paths in Aero-Engine Technology1893–2013

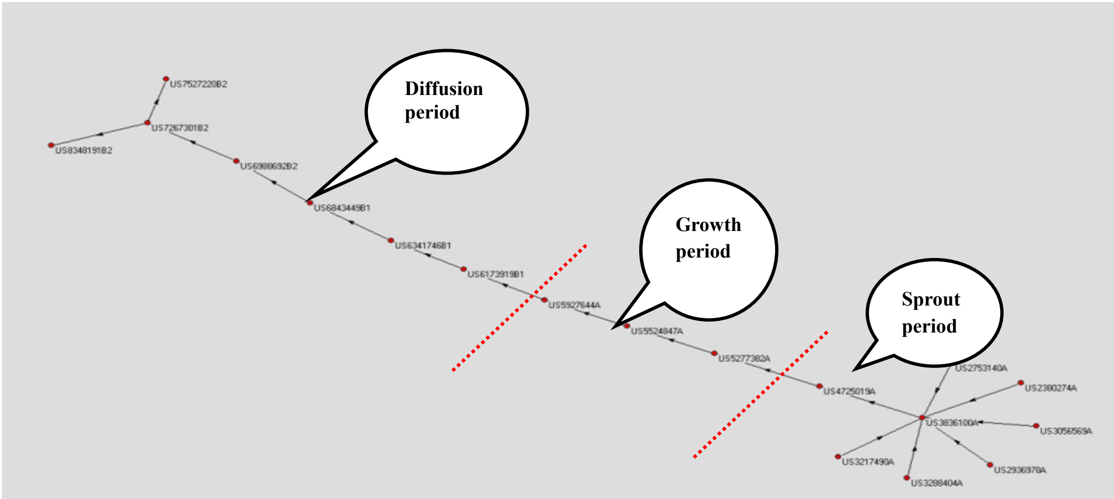

Fig.6. Aero-Engine Technological Trajectories

B. Interpretation of the technological trajectory

From figure 6 it is obvious that the technological trajectory is continuous without any gap. We can conclude that the technological evolution of aero-engine follows the principle of doing it step by step. Dosi [40] argued that incremental innovation is an improvement based on present technology, while breakthrough innovation will alter its original technological trajectory. Technological trajectory is just the process of combining both of them.

Based on the integral analysis on the number of patents in figure 4, we summarize the patent information and the character of patent technology in different stage of technology trajectory in Figure 6.

Sprout period-Transition from the Aircraft Piston Engine to Jet Engine (before 1970s) :

From figure 6 we can see that there are seven patents in this period, i.t.2380274, 2753140, 2936978, 3056569, 3217490, 3288404, 3836100. There are two features of technological evolution- First Piston Engine technology is significantly improved by part's standardization and serialization; then the technique is mainly applied to Aircraft Piston Engine, while in late Sprout period i.t.1960s-1980s,

Aircraft Piston Engine is gradually replaced by Jet Engine and the aero-engine technique develops into Jet Engine.

2380274 relates to mounting airplane engine in airplane. This invention fastens rear and front mounting under the high-speed operation, and it is mainly applied to Aircraft Piston Engine.**2753140** relates to the provision of an improved engine suspension means for connecting an engine to its support which minimizes deformation of the outer casing of the engine. **2936978**- This invention relates to mounting means and more particularly to the mounting of an aircraft engine within an airplane nacelle and provide mounting means at the rear of an aircraft engine. **3056569**-it relates to airplane engine suspension system for a turbo-propeller engine in an airplane and the individual vibration isolators or mounts.

Then technique of aero-engine develops into Jet Engine. **3217490**-it concerns the installation of jet engines in engine bays and boosting the performance of jet engine. **3288404-**this invention is an engine mounting system which provides longitudinal, vertical and lateral isolation and restrains rotational motion of the engine. It is an elevation of a mounting system for a turbo-shaft engine for driving a helicopter or a propeller. **3836100**-This invention relates to an aircraft engine mounting arrangement and more particularly to a helicopter engine mounting which isolates the roll response of the engine from lateral input motions from the helicopter airframe.

Growth period- Transition from Jet Engine to Turbofan (1980s- the end of the 20th century) :

4725019, 5277382, 5524847 on the technological trajectories are in this period. The features of technological evolution- the replacement of Aircraft Piston Engine by jet engine, - great improvement of jet engine technology even the Turbofan is invented and its technology is getting perfect.

4725019-This invention relates to aircraft engine mount systems and, more particularly, to such a system which includes vertically spaced upper and lower isolators that are flexible vertically to isolate vertical vibrations and that are stiff laterally to resist lateral loads and roll torque. **5277382-**This invention relates generally to aircraft mounted gas turbine engines, and, more specifically, to a mount for supporting an engine to a wing or tail pylon. The development of Turbofan is based on the Gas turbine engines research. **5524847**-This invention relates to aircraft propulsion systems and more particularly to a nacelle and mounting arrangement for aircraft engines. The ducted fan engines used in these propulsion systems are improved greatly.

Diffusion period- techniques developed into intelligent system (early twenty-first century-now) This period mainly include **5927644, 6173919, 6341746, 6843449, 6988692, 7267301, 7527220.**The features of technological evolution-the technique of Turbofan and turbojets gets mature enough and they develops into intelligent systems; the performance of aero-engine mainly improved by the use of intelligent systems.

5927644 The invention relates to a device for attaching an aircraft engine onto a pylon fixed to a wing or a fuselage. Double Failsafe engine mount begins to be used to perfect turbofan function. **6173919-**The invention relates to a device for attaching an aircraft engine onto a pylon fixed to a wing or a fuselage. In addition, the attachment device according to the invention is lighter than equivalent devices produced by previous technology, because of the reduction in size of the fitting. **6341746-**The invention relates to an attachment device for fixing an aircraft engine to a strut secured to a structural element of the aircraft, such as a fuselage or wing element. A preferred application relates to aircraft of modern design, whose engines are equipped with very large diameter fans. It mainly relates to a simplified attachment device usable in a novel fixing system for an aircraft engine. **6843449**- This present invention particularly relates to a fail-safe engine mounting system that transmits between the engine and aircraft axial thrust loads, as well as lateral and vertical loads, in the event of a failure of the main load-transmitting elements. When one or more of the links are no longer capable of transmitting loads, the fail-safe arrangement becomes operative to accommodate the loads transmitted between the engine and the airframe. This is one direction of automatic technology. **6988692**-This invention relates to the suspension of propulsion engines to an aircraft structure. It relates in particular to a suspension or rear fastening device including means for retaining the suspension in case of accidental breakage of one of its parts. **7267301**-The name of this patent is aircraft engine with means of suspension from the structure of an aircraft. It relates to the mountings of aircraft engines, and particularly turbojets. Its major advantage is ease of manufacturing, low weight, ease of inspection of the primary force path and capability of providing a safety function if one of the conventional force transmission elements in the rear mounting should fail, which once again increases the mass and size. **7527220-**This invention relates to a mount for aircraft engines, in particular for turbofan jet engines. On the pathway of the airstream passing through it, from upstream to downstream, an engine comprises an air inlet, a fan case, an intermediate case, a thrust mount, an exhaust case and an exhaust nozzle. This patent is remarkable in its capacity to ensure its failsafe function in all cases of failure. How to find the cases of failure mainly rely on intelligent equipment to achieve it. **8348191-** This invention -Fail-safe aircraft engine mounting apparatus, relates to aircraft engine mounts. More particularly, it mainly applies to turbofan engine and provides fail-safety.

TABLE I. OVERVIEW FOR PATENTS OF AERO-ENGINE ON THE PATH

Granted number	Title	Granted author	Apply time	Granted time
2380274	Airplane engine mounting	Rolland S. Trott, Denver, Colo.; Eleanor J. Trott	Nov, 4, 1940	July 10, 1945
2753140	Engine mount	United Aircraft Corporation	July 28, 1951	July 3, 1956
2936978	Rear engine mount	United Aircraft Corporation	Mar 29, 1957	May17, 1960
3056569	Airplane engine suspension system	Textron Inc	Sep 29, 1954	Oct 2, 1962
3217490	Installation of jet engines in engine bays	Rolls-Royce Limited	Apr 29, 1963	Nov16, 1965
3288404	Engine mounting system	Lord Corporation	Aug 24, 1964	Nov29, 1966
3836100	Engine mounting arrangement	United Aircraft Corporation	Jun13, 1973	Sep 17, 1974
4725019	Aircraft engine mount with vertical vibration isolation	The Boeing Company	Aug 11, 1986	Feb 16, 1988
5277382	Aircraft engine forward mount	General Electric Company	Oct 13, 1992	January 11, 1994
5524847	Nacelle and mounting arrangement for an aircraft engine	United Technologies Corporation	Sep 7, 1993	Jun 11, 1996
5927644	Double failsafe engine mount	General Electric Company	Oct 8, 1997	Jul27, 1999
6173919	Attachment device for an aircraft engine	Aerospatiale Societe Nationale Industrielle	Jan 26, 1999	Jan16, 2001
6341746	Device for attaching an aircraft engine	Aerospatiale Airbus	Apr24, 2000	Jan 29, 2002
6843449	Fail-safe aircraft engine mounting system	General Electric Company	Feb 9, 2004	Jan 18, 2005
6988692	Rear fastening device for aircraft engine	Snecma Moteurs	May 5, 2004	Jan 24, 2006
7267301	Aircraft engine with means of suspension from the structure of an aircraft	Snecma Moteurs	Apr28, 2005	Sep. 11, 2007
7527220	Aircraft engine mount	Snecma Moteurs	Mar 24, 2005	May 5, 2009

IV. CONCLUSIONS AND DISCUSSION

A. Contribution

To achieve the goal of understanding the evolution of aircraft engine technology, patent analysis is performed by seeking the citation among aircraft engine patents. Through analyzing the patent citation network and adopting SPLC values as statistical index, this study has brought out a technological evolution route i.e., technological trajectory. The findings of this study are summarized below by using patent bibliometric analysis and patent network analysis which are the quantitative analysis method and using technological lifecycle theory which is a qualitative analysis method.

First, the evolution of aircraft engine technology represents a phased characteristics (Fig.4) . Second, the development of aircraft engine technology is a process of incremental innovation, and the technology trajectory (Fig.2) is continuous without gap. Third, the technology trajectory can be divided into three stages: the first one is Sprout period, during which the aviation engine technology transformed from piston type to turbojet type; Growth period is when experts research the Turbofan technology and further deepen it. More kinds of turbofan engine are invented; Diffusion period is when Turbofan engine is still being used but all kinds of aircraft engine technology start to develop to the intellectualized direction.

B. Implications

The aim of this paper is to show the ways of identifying and mapping the technological trajectory from the citation networks of aircraft engine related patents. Analyses of these characteristics related to aircraft engine of different stages suggest directions for government patent strategy and technology policy and give research institutes, industries and academia useful guideline for choosing patent technology field in which they should invest. Some specific policy suggestions about how to realize technological breakthrough in the aircraft engine field are shown below.

1) As the evolution of aircraft engine is accumulative, enterprises should focus on the development of technological trajectory from its start and find out which factor has most influence, such as technology, government, economic and so on, and should also especially focus on the patents on the trajectory. So investors can adopt the policy of Introduction, Digestion, Absorption and Re-innovation, i.e. introduce Turbofan technology and quickly achieve the technological breakthrough.
2) The phased development requires the investors` technology strategy to be appropriate to the direction of technological trajectory and it should adjust it at the right time. It is particularly urgent for enterprises to decrease research spending on piston, increase investment in Turbofan, and adjust the direction to intellectualization.
3) Technological trajectory is composed only of existing patents, so researchers must have the ability to forecast accurately the direction of technology evolution, and avoid forming the path dependence and failure to seize the opportunity to take advantage of technological changes to enhance the capacity of the firm.

C. Limitations

Based on the technology life cycle, this paper has divided the evolution process of aircraft engine into different stages. The technological trajectory has been mapped by using patent bibliometric analysis and patent network analysis which are based on the quantitative analysis method. However, how the evolution of technology is achieved and why it evolves in this way are not mentioned. Therefore, we are collecting materials for aircraft engine and are trying to build a co-evolution module including R&D, enterprise, government, and University and so on, to interpret the evolution mechanism in different stages.

D. Future Research

It seems particularly promising to combine the quantitative analysis of citation paths with a detailed qualitative analysis of technology lifecycle. The analysis of patent citation can provide additional insights in terms of outlining the important main path of development and the interaction between different patents. As shown in the case of aircraft engine, this method can be used to extend the systematic understanding of technology changes for industries where patents are an effective way to appropriate innovations. In a word, our paper provides a framework for future empirical research, which will potentially have significant implications for academia and managerial practice.

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