# **The Factor and Logic of Technological Breakthrough**: A Case Study in Ship Technology

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## 1. Introduction

The purpose of this report is to clarify the factor and logic of technological breakthrough as a concept of discontinuous innovation through a case study of the history of ship technological development. The concept of discontinuous innovation has attracted attention in many previous studies, including the origin of the innovation in the technological paradigm shift of Dosi (1982). Technological breakthrough is a process of discontinuous innovation to exceed the limit of existing technology and is one pattern of the technological paradigm shift. However, this concept has not been discussed much to date. Furthermore it is the fact that discontinuous technological innovation such as the technological breakthrough is difficult to achieve, because of attachment to an existing technological paradigm. Therefore, in this report, I aim to clarify the factors and logic that determine whether it is possible to exceed the existing technology by investigating the development of the hydrofoil and bulbous bow, which are cases of an epoch-making technological breakthrough in the history of the evolution of ship technology that contributed to the acceleration of marine transportation, thereby playing a major role in the development of the global economy.

In a study of the history of marine transportation, this topic can clarify how ship technology achieved rapid acceleration in the early 20th century. In addition, the contribution of this report is that via an innovation process study, a new hypothesis of the process of discontinuous innovation technology can be demonstrated.

## 2. Previous research

The concept of technology is considered in this report. Arthur (2009) said, ‘Technology is always based on some phenomenon or truism of nature that can be exploited and used to a purpose’. Namely, it is necessary to control a phenomenon precisely in order to utilise it as technology. Therefore, I define ‘technology’ as knowledge of the control method for a factor that can be set to intentionally achieve a certain aim by allowing a change in the state of the material. In addition, I define a technology factor as the factor used to control a given technology. On the other hand, I define ‘science’ as the systematic and theoretical explanation of the outbreak mechanism of natural phenomena by deduction of the existing physical or chemical theory, and thus distinguish science from technology.

I define technological accumulation as the relationship between various technological factors, a concrete control method of technological factors, and the accumulation of knowledge of the technological mechanism, that are clarified during the process of technological development.

Technological innovation is when new technology is developed that can realise a function, performance, quality, or productivity that could not be accomplished using an existing technology, and continuous and discontinuous patterns of technology innovation have been discussed. Dosi (1982) explained a continuous change in the technological development as a representative previous study with the framework of the existing technological paradigm and explained a discontinuous change with a new technological paradigm shift. Continuous innovation refers to technological evolution in the range that can reason from existing technology and science. Discontinuous innovation refers to the rapid evolution of technology that cannot be reasoned based on existing technology and science.

As an evolution pattern of discontinuous innovation, Foster (1986) showed another discontinuous

S curve that newly appeared after limiting the arrival of the innovation. A characteristic of this discontinuous S curve is that it exceeds the limit of the existing technology by the introduction of new technology, and the arrival level of the new technology is greater than that of the existing technology. Hence, the new technology first overtakes the level of the existing technology by evolution. However, in addition to the discontinuous S curve, the limit of the existing technology is exceeded by applying a new idea to an existing technology, which may, for discontinuous innovation, achieve an unprecedented high aim. I define this as a technological breakthrough. Typical cases of the technological breakthrough include the crystal-growth technology of gallium nitride, which is the material of the blue light-emitting diode (Amano, 2015), and a conductive high-polymer composition technology (Shirakawa, 2001), which won the Nobel Prize. The growth curve of the breakthrough is large and surpasses that of the existing technology from its initial development, despite lacking the S-curve evolution process. Discontinuous S curve is produced independently and evolves afterward, rather than arising from the S curve of a previous technology. Furthermore, a key difference from continuous technological innovation is that breakthroughs establish a new technological framework through a new technological idea that cannot be reasoned from the previous framework.

The significance of the technological breakthrough lies in the creation of technology believed to be unrealisable and founding new industry by meeting needs that were not previously recognised, which can revolutionise the existing industry (Stefik, 2004). Furthermore, the speed of the technological advancement is rapid because it can build upon existing technological accumulation with the new growth curve arising from the existing S curve. Technological innovation by a new S curve requires new technological accumulation; therefore, a judgment of the resource injection and time to technological advancement becomes a problem.

However, it has been cited that it is difficult to achieve discontinuous innovation technology based on the existing technological framework because of attachment to an existing technological paradigm (Leonard, 1995; von Tunzelmann et al., 2008).

Therefore, as explained by the previous study, there is a limit upon the development of new ideas that cannot be reasoned based on the existing technological accumulation to produce a technological breakthrough.

In real technological development, how will the innovation of technology via breakthrough be created? New technology is formed by many empirical methodologies rather than necessarily being created for technological deductive extension (Rosenberg, 1982, Polanyi, 1966). In the technological breakthrough, it is thought that a new innovative technology is rebuilt based on an encounter with a new solution by starting after a deadlock in the technological development based on existing technology. There are two patterns of encountering new solutions: serendipity and technological inspiration. Here, technological inspiration is to find the hidden technological factor and draw a summary of the mechanism of the phenomenon for a solution (Uchiumi, 2017). There are more arguments on serendipity (Itami, 1986; Fujii, 2002; Miyanaga, 2006; Shiga, 2015), but the probability of encountering a solution by this method is extremely low because technology has many complicated intertwining factors. Though an engineer may consider a technological inspiration and strive to bring about an unprecedented new technological idea, this subject has not been mentioned much in the literature to date. Therefore, I focus in this report on technological inspiration to create technological breakthroughs and aim to clarify the corresponding factors and logic through a case study.

There are many previous studies how new ideas, such as technological inspiration, are born. According to Schumpeter (1926), the innovative phenomenon is caused by new combination of existing phenomena. In addition, according to Young (1986), the new idea is a combination of existing related phenomena. Therefore, the technological inspiration set the hypothesis model of a new key technological factor is combined for the existing technological accumulation (Fig.1).

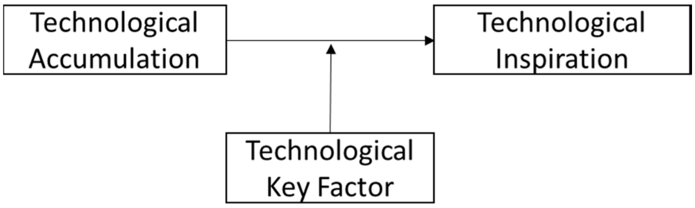

Fig.1 Technological Inspiration Model

Therefore, the framework of the analysis in this report is based on a hypothetical model of a technological breakthrough that occurs by the combination of the existing technological accumulation and new key technological factor. I investigate and consider the following questions through a case study: what is the existing technological accumulation, what is technological inspiration, and where do the new technological factors come from?

## 3. Case study

I chose a case study for the derivation of a new hypothesis (Yin, 1994) and mainly investigated based on a primary document (book, article) written by a developer as the evidence source for the cases. Objectivity was secured by use of a second document (Yin, 1994). I chose the history of the technological development of ships, which contributed to marine transportation and played a major role in the development of the global economy, as a case. The reason for the choice is that a technological breakthrough as the result of steady research of safety and economy exists during the history of the technological development and size of the technological accumulation of ships based on the extent of the risk due to the marine environmental uncertainty and path-dependent height.

The beginning of the history of ship technology dates back to B.C. However, sudden development was accomplished by the first wave of globalisation starting in the Industrial Revolution of the 1800s, after the 1600s, when ship technology began to develop rapidly in the Age of Geographical Discovery. One of the major factors that enabled this acceleration of globalisation was the dramatic shortening of the geographical distance due to the technological advancement of ships to transport many loads and passengers faster (Jones, 2008). The increase in the speed of ships accelerated globalisation, which in turn accelerated the technological development to further speed up larger ships.

The technology that increased the speed of the ship is the propulsion technology and hull technology. When a ship floating in the water advances, the ship is affected by the resistance of the water. Therefore, a propulsion technology superior to this resistance and hull technology to reduce this resistance are necessary to navigate a ship faster. It is natural that stronger propulsion technology is important, but it is also an important technology to reduce the resistance (frictional resistance, wave-making resistance, whirlpool resistance) of the water based on the hull shape (Yoshida, 1976, Ouchi, 2017).

For a long time, the history of the ship was itself a continuous evolution of the sailboat. Related factors include the hull-supporting materials, shape, number of sheets of the sail, and mast. This led to the Age of Geographical Discovery in the 17th century, and the sailing boat that could carry many supplies and endure the extended navigation developed. However, the speed of the sailing boat was slower than that of a modern ship and was approximately 10 knots in favourable wind.

In the early 19th century, when the importance of sea traffic to the United States and the Chinese tea import of the U.K. increased, the short-term increase in ship speed was great. The speed increase with the sail as the propulsion technology reached its limit at that time. However, it became possible reach speeds of approximately 15 knots by increasing the aspect ratio of the ship (Ouchi, 2017).

As for the steam engine, which produced the Industrial Revolution, its introduction was attempted on a marine ship. The original purpose was to remove dependence on the direction of the wind and strengthen, rather than speed up, the ship. The development of the steam reciprocating engine advanced as the new stable power for navigation. These power vehicles evolved from an original outer ring type to a screw, and the speed increase advanced rapidly, enabling a speed of approximately 25 knots. The steam turbine engine, which was more powerful than a steam reciprocating engine, was developed in the early 20th century and spread widely. The evolution of the propulsion technology depends on the range of the new S curve of a steam reciprocating engine and the steam turbine engine, as shown in Fig. 2, which follows a trace of the Blue Ribbon Award for the mean navigation speed of a transatlantic route of a passenger ship (Newman, 2008, Ouchi, 2017).

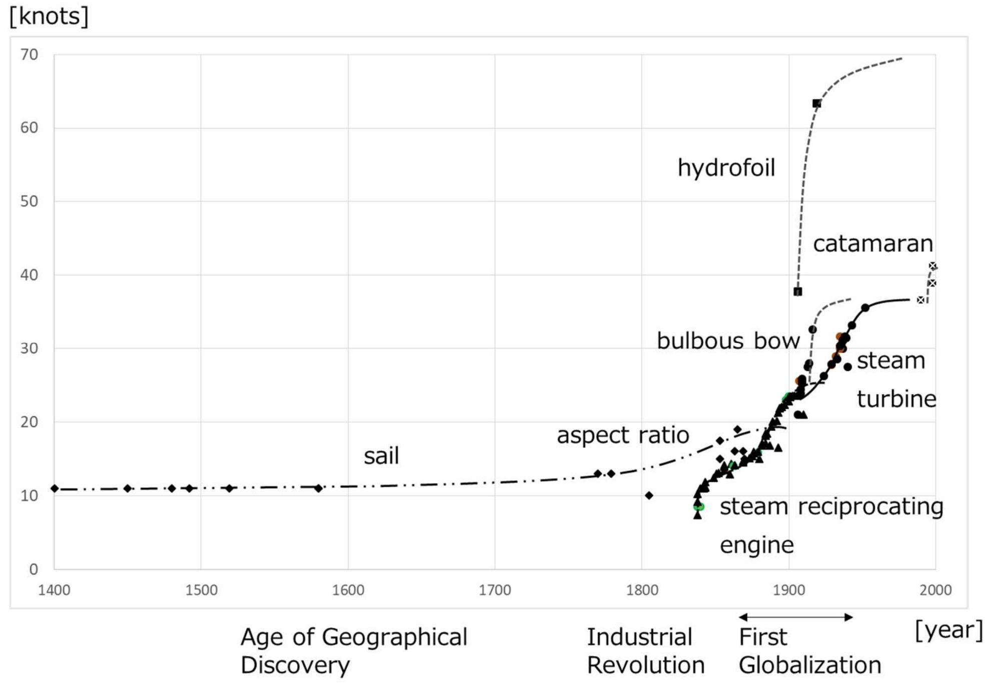

Fig.2 The history of ship speed up

Innovative technology, such as the bulbous bow, hydrofoil, and catamaran, lay a new growth curve on the existing S curve in a hull technology, whereas a propulsion technology draws another S curve. This could possibly be called a technological breakthrough.

Therefore, in this report, I choose the hydrofoil and bulbous bow as representative cases of the technological breakthrough that arose in the history of the development of hull technology. There are two reasons for this selection. The first is that a technological breakthrough corresponding to the need for increased ship speed was born from the large technological accumulation in the history of the development of ship technology. Simulations based on hydrodynamics and experience of the complexity of fluid behaviour is indispensable to the design of the hull shape, and the path dependence on existing technological accumulation is high. The second reason that it is thought that it is difficult to create a technological breakthrough.

The hydrofoil is a type ship that adopted the epoch-making hull technology that can greatly reduce the resistance of water, by lifting the hull surface from the water. This supports increasing the speed of passenger transportation, and it may be said that it is a case of achieving a technological breakthrough to greatly exceed conventional navigation speed by coupling an existing ship technology and the lift-control technology of wings. The concept of a hydrofoil was first conceived in an experiment with a small model ship, performed by Thomas Moy in London in 1861. An ingenuity was added to the shape of the hydrofoil but was not stable; a full-scale ship surface was developed about half a century afterwards. The cause was that the lift from the water was proportional to the square of the speed, and area of the surface greatly changed when the speed changed, which made it difficult to maintain stability of the surface. Forlanini, an Italian aviation engineer who developed the helicopter and airship, solved this problem through his familiarity with control technology in fluids. Therefore, the problem of the lift change with respect to speed was considered, and the solution was inspired by the ladder foil, which is able to provide lift approximately constantly even as the speed changed due to the hydrofoil of multiple pieces. Stable navigation by the full-scale ship was realised by the examination of navigation in Lago Maggiore in 1906, and a record speed of 38 knots greatly exceeded the speed of the steam turbine ship at the time. The success of the hydrofoil by the ladder foil immediately resulted in the concept of the consecutive lift control by the V-shaped wing, and a model of the modern hydrofoil was completed. In 1910, Alexander Graham Bell was impressed with Forlanini's hydrofoil began development of a patent license. A very-high-speed passenger boat of 61 knots was realised in 1919, and the hydrofoil was spread afterwards to the world (L. Yun and A. Bliault, 2012; J. Meyer, 1990).

The bulbous bow was suggested by D. W. Taylor in 1910. It can reduce the wave-making resistance of a large ship, such as a large passenger ship, warship, or carrier, by the epoch-making hull technology that can increase the speed with low mileage. The hydrofoil was a hull technology to realise unprecedented high speed, but it was not suitable for large ships with high weight, so a different technological breakthrough was necessary. The bulbous bow is a technological breakthrough that can largely reduce the resistance from the waves simply by adding a projection to the lower part of the existing bow, which was able to exceed the limit of the existing hull technology that could not consider the extension of the existing wave-making resistance reduction technology. D. W. Taylor was a ship-building engineer in the United States Navy. He improved the speed of the ship and its propulsive relations from the accumulation of the existing hull technologies and demonstrated this improvement by experiment with the examination water tank (basin). However, the limitation in the speed improvement due to wave resistance greatly impacted the solution. Therefore, the bulbous bow was inspired by the ram bow (D. W. Taylor, 1910). The ram bow was a projection equipped on the tip of ancient battleships, and its purpose was to puncture a hole in enemy battleships. It was realised that there was little impact from waves on the bow section of ships using the ram bow. Thus, it was believed that the wave resistance could be reduced similarly using the bulbous bow. The bulbous bow was tested with an examination water tank (basin) and the effect was confirmed by inspection. The bulbous bow was adopted in 1910 on the U.S. battleship Delaware and, including a warship of U.S. Navy Lexington-grade carrier in 1927 nest, was adopted on a warship and the passenger ships of each country. The mechanism of technological breakthroughs that offset resistance by effecting a phase difference for the wave-making resistance and hull resistance has become clear through proof, as does the theory calculation for real ships becomes clear. The bow shape of large ships became standard afterward (Carlisle, 1998).

## 4. Consideration

As a result of investigating the history of development of ship speeds, the evolution of the propulsion technology is understood to have progressed from the steam reciprocating engine to a range of new discontinuous S curves, such as those of the steam turbine engine and sailboat. Because the evolution of one such hull technology was an idea that could not be developed directly from the extension of existing technology, based on the case study of the hydrofoil and bulbous bow, and because a new growth curve to greatly surpass an existing technology from conception was created without passing through the evolution process of a new S curve, it is possible to confirm that it was a technological breakthrough. In other words, the innovation that occurred during the first wave of globalisation in speed increase of ships was brought about by the discontinuous S curve of the propulsion technology and the breakthrough of the hull technology.

Therefore, I separately consider the motive and the main reason for the breakthrough factors of these hull technologies. First, consider the motive of the external and internal factors. External factors include the distribution quantity after the Industrial Revolution as the background, and the improvement in the speed and hydrodynamic completion as the technological background, and the recognition of the limit of propulsion technology at the time. One internal factor includes the recognition of the limiting factor of wave resistance and framework of scientific theory (hydrodynamics, hull studies), i.e., the limitations of the existing technology.

Next, I consider the framework of analysis as a main factor in how the technological breakthrough was born. There was the ceiling that could not be exceeded by changing only the existing hydrofoil, namely the stability of the lift during speed change, whereas there was endogenous technological accumulation of the hydrofoil through many model experiments and research on the limit. Therefore, Forlanini analogised a key technological factor, the number of wings, from the navigation stability technology of airships for lift control against acceleration, and was inspired by the idea of the ladder foil, resulting in the multistage hydrofoil. The key technological factor is different from that of the hull technology, but it was associated with related aerodynamic design technology, namely the exogenous technological accumulation in hydrodynamics.

In the case of the bulbous bow, there the limit could not be exceeded by the curved shape that was hung aft, and the resistance of the waves caused problems for the high-speed navigation of vessels with high load capacity and aspect ratios. The bow of the ship in the endogenous technological accumulation of hull studies was researched to find a method for the limit breakthrough. Therefore, Taylor found a key technology factor involving a projection of the lower part of the bow based on battleships with ram bows, which inspired the bulbous bow. The ram bow was a technological accumulation to puncture the hulls enemy battleships, and was thus an exogenous technological accumulation, but a key technology factor was also associated with it.

Therefore, from the breakthrough example of two of the hull technology, the following three results became clear. First, the limit of the existing technology was exceeded by a technological inspiration. This technological inspiration was born in combination with a endogenous technological accumulation and new key technological factor. Furthermore, the new key technological factor was provided by an analogy from exogenous technological accumulations. The endogenous technological accumulation is the technological accumulation in the specialised technological field of concern. An exogenous technological accumulation is the technological accumulation in a specialised field other than that of primary concern. This concept is expressed in Fig. 3.

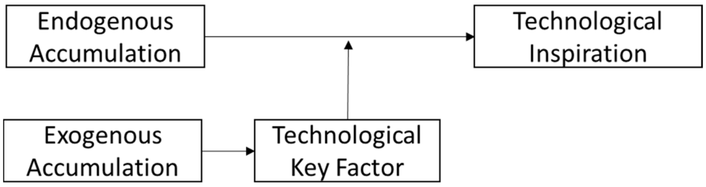

Fig.3 New Technological Inspiration Model

In fact, existing technological accumulation is important, and it is in this way thought that the role of endogenous and exogenous technological accumulation in technological inspiration was suggested as a new hypothesis to exceed the limit of existing technologies in a technological breakthrough.

## 5. Conclusion

In this report, I obtained new hypothesis on the factor and logic of technological breakthroughs through a case study of the historical technological development of ships. The motive of the technological breakthrough in ship technology was the hope for the existing technology to be improved through external and internal factors. The main goal for this is to exceed the limit of existing technology via technological inspiration to obtain a new solution. Technological inspiration is born in combination with the endogenous technological accumulation and a new key technology factor. Furthermore, it became clear that the new key technology factor was provided by analogy from exogenous technological accumulation. In this way, the contribution of this report was to clarify the process of technological breakthrough in technological paradigm shifts and the relationship between existing technological accumulation and the technological paradigm shift. In addition, in the context of the important role of the innovation of ship speed in marine transportation in the first wave of globalisation, it is another contribution of this report that the innovation of the propulsion technology can be explained by the appearance of another discontinuous S curve, and the innovation of the hull technology can explained by a technological breakthrough.

However, this report is a hypothesis in a limited case, and inspection by multiple case studies and elaboration of the logic will be necessary in the future: more study is demanded. In addition, continuous study is expected in the future, including the applicable confirmation of the reference to the process and other examples without enough arguments for the technological inspiration considered in this report.

Finally, it is important that engineers and managers of technological development aiming at technological breakthroughs should understand the important role of technological accumulation. As for the importance of the combination of technological factors from endogenous-accumulation-based exogenous technological accumulation, it is thought to be an effective suggestion for the technological development to obtain a rapid solution. It is expected that future work will provide deeper consideration and confirmation of the effect in practice.

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