

Early Times of Fluid Mechanics in Japan: Terada, Tani, Imai, and Aeronautical Research Institute

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ABSTRACT

Science history of fluid mechanics research in Japan is reviewed for the time during the first half of 20th century. Three distinguished persons, Torahiko Terada, Itiro Tani and Isao Imai, were more or less associated with the Aeronautical Research Institute. Before the establishment of the Institute, von Karman and Prandtl were invited to the Institute to give series of lectures.

Terada discovered a sequence of rolling eddies in the boundary layer cooled from above (or heated from below). Tani studied wing shapes and proposed a new wing which keeps its boundary layer laminar as long as possible. Imai resolved a paradox of divergence problem in an asymptotic solution starting from the Oseen equation, for a flow around a solid body placed in a uniform stream.

Key Words: Science History, Terada, Tani, Imai, Aeronautical Research Institute

1. Introduction

When we look back the first half of 20th century of fluid mechanics research in Japan, we find a number of remarkable studies. Three distinguished persons, Torahiko Terada, Itiro Tani and Isao Imai, were more or less associated with the Aeronautical Research Institute of Tokyo Imperial University. Before establishing the Institute, von Karman was invited to the Institute to give a series of lectures on contemporary researches of aeronautics and fluid mechanics in 1927, and in 1929 Prandtl too gave three-day lectures there. Soon after, a 3-meter-wind-tunnel of Göttingen type was constructed at the Institute of its new campus of Komaba.

2. Torahiko Terada (1878 -1935)

Terada (Fig.1) was a physicist, geo-physicist and an essayist, and good at making witty remarks. One of his well-known remarks is “*A natural disaster is likely to occur at such a time when people forget it*” (1934). This was a warning to the government which was preparing war. Another one is: *A diamond can be processed to a jewel once it is dug up in the rough. However, glass is unable to be finished into a jewel* (1931). He was warning scientists in general after resigning professorship at Physics Dept (Tokyo Imp. Univ.), but keeping his positions at three research

institutes. He published a paper with second-year students of Physics, “*Some experiments on periodic columnar forms of vortices caused by convection*”¹⁾. Terada recollects, “About ten years ago, it happened to observe the following :

Aluminum powder was mixed and suspended in alcohol. It was spread on the plane bottom of shallow basin, so as to form a thin layer of about 1 mm depth. On tilting the vessel, the liquid mixture flowed down along the plate bed. The powder is arranged into sharply defined bands, consisting of fine filaments running in the direction of liquid flow. Thus, he observed convective roll patterns of flow cooled by evaporation at surface, which was much earlier than studies in the west.

Terada’s experiment (1928) is now understood as a thermal boundary layer. The roll pattern (Fig.3) can be observed as filamentary cloud patterns of cold front flowing over warm moist-rich surface of the Japan Sea, by the satellite photo in winter time. Expressing perturbations by forms proportional to $\exp[\lambda t + iky]$ (where t and y

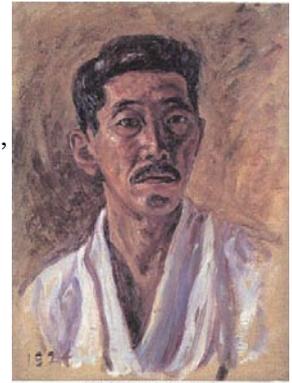


Fig.1 Self-Portrait
(T. Terada).



Fig.2 Convective roll pattern of water flow over heated bottom (Terada, 1928).

are time and horizontal coordinate, k the wave number, λ a constant, i the imaginary unit), one can write linear perturbation equations as follows:

$$(D^2 - a^2 - \lambda)T = -W$$

$$(D^2 - a^2)(D^2 - a^2 - \lambda/P)W = a^2 R_a T$$

where T and W represent variation amplitudes of temperature and vertical velocity, Ra the Rayleigh number, Pr the Prandtl number, and $a = k / \delta$, δ the thickness of boundary layer.

The above two equations are equivalent to the perturbation equations of Görtler problem, if we replace T and W with tangential and radial components of velocity (see Drazin and Reid, Ref.9). Terada's experiment was earlier by more than ten years than Görtler's work. (1940).

3. Karman and Prandtl in Japan

In 1921, the Aeronautical Research Institute was established in Tokyo Imp. Univ.. Koroku Wada (much later, to become its director) visited Europe from 1919 to 21, and met Prandtl and von Karman in Germany. When returned, he was asked: *Who is the best person to be invited for the sake of developing aeronautical research in Japan?* According to Iitiro Tani, Wada replied, "Prandtl". After the suggestion, an executive of Kawanishi (Aeroplane Company) visited Göttingen and tried to invite Prandtl to Japan. Prandtl suggested him to speak it to young von Karman. According to Karman's memoirs, his mother was reluctant to the offer, since there was another offer from USA as well. In order to decline, he required his reward to be doubled. Unfortunately, it was accepted. Karman (1881-1963) visited Japan in 1927. His monthly salary was ¥1,000 (when a high rank professor received ¥400. monthly). He gave a series of lectures on Aeronautics²⁾. The subjects were, (a) *Theory of propellers*, (b)

Flight performance, (c) *Stability of airplanes*, and (d) *Aerodynamics forces and vibration*.

Prandtl visited Japan too, in 1929 when an international congress of industries was held in Tokyo, and gave a lecture at the National Diet Building, on "The Role of Turbulence". At the Aeronautical Research Institute, he gave three lectures (Oct. 1929)³⁾: (i) *Turbulenz und ihrer Entstehung*, (ii) *Flüssigkeits-Strömungen: die Geschwindigkeit von der Grössenordnung der Schallgeschwindigkeit*, (iii) *Entstehung der Wirbel*.

Soon after, a 3-meter-wind-tunnel of Göttingen type (Fig.3) was constructed in the restarted Institute at the new campus of Komaba. Amazingly, it is still working at the same place.



Fig.3 Three-meter-wind-tunnel (March 25, 1930).

TANI once recollects: *An evidence of Log-law of turbulent boundary layer was first obtained in Japan.* In the paper of von Karman on the famous Log-law of velocity of the turbulent BL, Karman cited Wada's experimental work measuring turbulent friction drag, obtained in Japan. He regarded it as an experimental evidence for his derivation of Log-law. Tani writes: *I felt that I saw his deep insight and moral of a scientist.*

4. Research Development: KOKEN-KI (航研機)

Long-range Research-Plane named Koken-Ki (Fig.4: width: 27.93m, length: 15.06m, maximum speed: 245Km/h) was developed by the Aeronautical Research Institute (Tokyo Imperial Univ.). This plane accomplished the world record of *Non-Stop Flight-Distance* in 1938. This was the first big project of scientific research in Japan. According to the web-illustration⁴⁾, the flight was as follows.

Time was 4:55 early in the morning, May 13th, 1938. Wind was against with 1.4 m/s. Over-running the runway, the KOKENKI



Fig.4 KOKEN-KI (Aero-Institute-Plane)

finally floated the wing of the crimson (red) on the air. After three-day non-stop flight of 29 turns of a triangular closed flight course (Fig.5), it landed on May 15th, 1938, 7:20 p.m. with establishing the world record of total flight distance 11,000 km. Its speed of 186 km/h (over 10,000 km) was recorded officially. When it landed, its fuel was left sufficiently with 500 L.



Fig.5 Triangular flight course (Kanto, Japan).

5. Itiro TANI (1907–1990)

In 1940, Tani and Noda⁵⁾ proposed an LB24 wing, and Tani and Mituisi⁶⁾ tested experimental performance of LB24 (LB: Light-Blue, symbol color of Tokyo Imp. Univ.). Laminar wing LB24 (Fig.6) has a maximum thickness of $0.1c$ at the position $0.5c$, where c is the chord length, so that the minimum pressure occurs at a downstream position, while in the

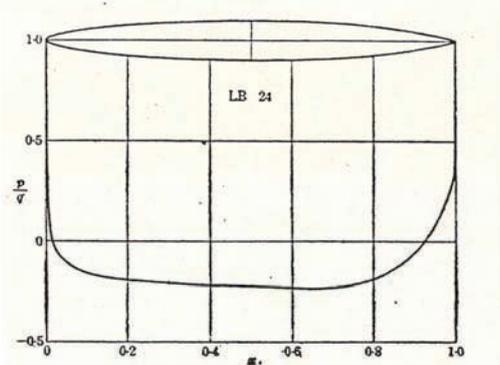


Fig.6. Laminar Wing (upper)⁶⁾. Pressure vs. chord (lower).

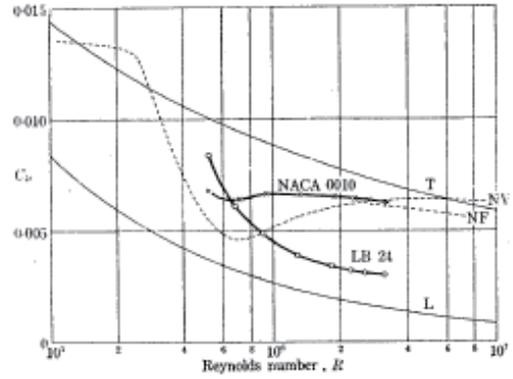


Fig. 8. Variation of drag coefficient of the two symmetrical aerofoils with Reynolds number. The curves L and T represent the drag of a flat plate when the boundary layer is entirely laminar and entirely turbulent, respectively. The curves NV and NF represent the drag of the aerofoil N.A.C.A. 0009 tested in the N.A.C.A. Variable-Density Tunnel and Full-Scale Tunnel, respectively.

Fig.7. C_D vs. Re - diagram⁵⁾

conventional design the thickest part is at 25% chord. The wing section LB24 is designed so as to maintain laminar flow throughout a greater part of boundary layer of the wing. An aerofoil that is likely to delay transition from laminar to turbulent flow in the boundary layer will be that in which the lowest pressure occurs well back along the surface. Tani was 33 years old at this time (See Fig.7 for C_D).

Later, the laminar wing was used in a water-plane 強風 (Gale). In the next stage, it was adopted in 紫電 (Purple Lightning, an airplane). In 1943, Prof. Matsui (松井辰弥先生) designed 飛燕 (Flying Swallow) No.2, but with a wing section of NACA Series.

6. Isao IMAI (1914–2004)

Imai once recollected his young times in his own article, *Recollections of a Fluid Physicist*⁷⁾. He had a special interest in exact solutions to the Navier-Stokes equation from early times of his career (from 1936) of fluid mechanics. In 1951 when he was 37, Imai published a paper⁸⁾, “On the asymptotic behaviour of viscous fluid flow at a great distance from a cylindrical body, with special reference to Filon’s paradox”.

This was a very successful and influential work.. An analytical solution to the steady Navier-Stokes equation, $(u \cdot \nabla)u = -\nabla p + \mu \Delta u$, is sought with successive approximations. He started from a solution to the Oseen equation:

$$U \frac{\partial}{\partial x} u = -\nabla p + \mu \Delta u$$

which is thought to be valid asymptotically at great distances. Note that the Stokes equation,

$$0 = -\nabla p + \mu \Delta u$$

is valid at small distances:

One of his motivations was to resolve the Filon's paradox (1928), which says that the moment of force on a cylindrical body placed in a viscous stream, with nonzero lift, diverges logarithmically by the term ϕ_2 of expansion for the stream function Ψ ($U\infty$ denoting uniform flow U):

$$\Psi = Uy + \psi_1 + \psi_2 + \dots$$

He posed a question himself whether the solution which Filon used is really meaningless, for a viscous flow around a solid body, which is the second approximation next to the Oseen's solution for a sphere (1910) and Lamb's solution for a cylinder (1911):

Carrying out successive Oseen expansions to the next third stage ϕ_3 (of the order of $1/r$, where r is the distance from the body), Imai was able to show that no divergence occurs, and corrected an error of the previous study of Filon:

$$\Psi = Uy + \psi_1 + \psi_2 + \psi_3 + \dots$$

Thus, Oseen type of successive approximation is useful in solving the Navier-Stokes equation for viscous flows and gives a valid solution of far field.

It was well-known at his times that, for uniform viscous flow around a cylindrical body (2D problem), the velocity of solution of the Stokes equation diverges logarithmically with increasing distance, called the Stokes paradox.

On the other hand, there is a solution of the Stokes equation for a sphere (3D problem). However, there is no next-order approximation which behaves appropriately at infinity: Whitehead paradox (1889) for a sphere. Validity of Stokes solution is limited to a near field.

Imai's work is understood in two ways. Firstly, it is related to how to find a solution uniformly valid over whole field for a viscous flow past a cylinder in a uniform stream. Imai's exact asymptotic expression provided a base to solve numerically the Navier-Stokes equation for a viscous flow past a body.

In fact, one of his research assistants (M. Kawaguti, later, Professor, Keio Univ.) carried out numerical computation of a steady flow past a circular cylinder in a uniform stream at a Reynolds number 40 (with respect to the diameter) by using a hand-calculator (Tiger). It took about one year and a half for him to obtain a final result (1953). This was a very successful achievement of direct numerical simulation of the Navier-Stokes equation which succeeded in visualizing standing eddies behind the body for the first time, well before the computer age from 1980.

From mathematical point of view, there remains still an essential obstacle. Although the Oseen approximation gives a valid asymptotic solution at large distances, it is

well-known that the boundary layer thickness adjacent to a solid body at a high R is scaled as $1/R^{1/2}$, whereas the Oseen solution gave the thickness erroneously scaled as $1/R$.

Thus, an idea of *decomposition of flow field* came up to the surface logically. *Near-field* is to be solved by the Stokes equation, while *far-field* to be solved by the Oseen equation. This formidable problem was resolved by the method of matched asymptotic expansions later in 1957 by two groups. The works of Imai (1951), and Tomotika-Aoi (1950) are cited by the paper of Proudman and Pearson (1957).

In summary, the numerical achievement of Kawaguti (1953) paved a path to finding uniformly valid solution of the Navier-Stokes equation, because his numerical result was the near-field solution to the Navier-Stokes equation matched to the far-field solution of Imai's solution. Moreover it coincided with the experiment of Taneda (1956). All these works of Japanese scientists were published before the year 1957 of the celebrated papers of the matched asymptotic expansions by Proudman-Pearson and Kaplun-Lagerstrom.

4. Summary

When we look back one hundred years of development of fluid mechanics research in Japan, we find a number of studies which were original and keeping their influences on the present age.

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