International Journal of Fluid Machinery and Systems
Vol. 9, No. 1, January-March 2016
DOI: 10.5293/IJFMS.2016.9.1.017
ISSN (Online): 1882-9554

Review Paper

Genesis of Researches on Surges in Pumping Systems in Japan

Nobuyuki Yamaguchi[1] and Yoshinobu Tsujimoto[2]

[1]Department of Mechanical Engineering, Meisei University (retired)
2-1-25, Akanedai, Aoba-ku, Yokohama, Japan, 227-0066, yamaguchi_nandm@tk2.so-net.ne.jp
[2]Mechanical Science, Engineering Science, Osaka University (retired)
2-3-27, Sakuragaoka, Minoo, Osaka, 562-0046, Japan, tujimoto@me.es.osaka-u.ac.jp

Abstract

Researches on the mechanism of surging and the surge behaviors in the systems of pumps, or fans or compressors, and the effects of flow-paths had been initiated and had made a great progress in Japan in the decades from the nineteen-forties to the nineteen-sixties. In 1947, the essential cause of the surges, i.e., self-excited oscillation nature of the flow-system, was discovered analytically by Professor Sumiji Fujii of Tokyo University, and most of the characteristic behaviors of the phenomena had been explained clearly. Successive studies by many other Japanese researchers continued to prove experimentally the mechanism, to extend the analytical studies, and to attempt preventing surge occurrence, etc. in the following two decades.

The historical information on the early surge studies could be helpful to some concerned people. At the same time, the basic and plain ways of discussions and reasoning about the phenomena in the pioneering researches could give us much to be learned even in the present time of high-power computing systems. Regrettably, many of the original research works have been published only in Japanese. The present review introduces very briefly the situations in memories of the pioneering researchers and engineers.

Keywords: Surge, pumps, compressors and fans, self-excited oscillation, pressure-flow characteristics

1. Introduction

It is said according to a comment in Ref [25] that, prior to 1940's, the surging phenomena, i.e., global instabilities of the system of pumps or compressors or fans, had been felt as "goblins" by most of concerned people. It suggests probably the ominous atmosphere that the phenomena whose cause had not been understood at all tended to haunt at unexpected times and occasions, making the people on the site struck with terror. Although the phenomena had been known by experiences since long time, their cause and mechanism had not been identified as late as 1940's. Therefore, the countermeasures were temporary ones reflecting the temporary experiences that could not have been theoretically consistent (Fujii [1]). By the way, the world first axial-flow compressor was manufactured in 1901 by Parsons.

The causes suggested at those times included various ones, such as, instability related with the pump characteristics, flow reversals in the pump, periodical separations of vortices, unstable separations of flow, etc. Self-excited oscillation was also suggested. None of them, however, could explain the phenomena consistently and decisively.

Fujii [1] considered that, since the phenomena were clearly periodical, they should be studied naturally from the aspect of vibrational sciences. In 1947, Fujii [1], in the discussion of the dynamic stability and oscillations of the system, introduced both the characteristics of the pump and the flow-path system to the flow rate, and the inertia effects of the fluid mass contained in the flow-path system, either of which had not been paid attention to in the foregoing studies on the surge phenomena. Thus, he could have identified in the very early time the surge phenomena in the pumping systems as a self-excited flow oscillation related with the positive-slope pump characteristics. In other words, Fujii [1-4] were probably the first papers, as far as we are aware, that have clarified the essence of the surge phenomena as the self-excited flow oscillation. It is a very important achievement that has started the surge studies in Japan and possibly in the world.

According to the results, the pump surges are explained as a relaxation oscillation resulting from the dynamic instability in the neighborhood of the equilibrium point, and many other features including the observed facts and experiences that the surge

Received September 8 2015; accepted for publication 3 October 2015: Review conducted by Kwang-Yong Kim, PhD. (Paper number O15045K)
Corresponding author: Nobuyuki Yamaguchi, yamaguchi_nandm@tk2.so-net.ne.jp

periods are independent of the pump speeds, surges include higher harmonic frequencies and periodical shocks, and so on, could be given consistent explanations.

Soon after Fujii [1-4], many further studies on surges in systems of not only pumps but also fans or compressors were conducted by the researchers as listed in the reference at the end of this review. Those researches have provided unified understandings at least in principle for surge phenomena in various situations. It might be not too much to say that the initial phase of the surge researches ranging widely from the basic pump systems to systems of multistage axial flow compressors has been accomplished by Japanese researchers.

Particularly, the basic and plain reasonings and discussions of Fujii [1-4] have revealed the essence of the phenomena. Katto [24], who in 1967 reviewed Fujii papers [1-4], praised that the reasonableness and extensiveness of Fujii's discussions were surprisingly excellent, even with the eyes at the review time. It could give us many lessons even in the present time of high-power computing systems that enable detailed numerical studies in a very short time. The authors believe that the papers are worth introducing to the present-day researchers.

Regrettably, Fujii and other researchers appear to have published the achievements only in Japanese. Now, the authors would like to try to introduce the related papers at the time, wishing to make clear the temporary status of the surge researches.

2. Introduction of the Analysis by Fujii - Surge of Pump Systems

Let us cite the most essential part of Fujii [1-4] along the line of the original paper. The essential part of Fujii [1] is translated below nearly word-for-word by the authors.

Copies of original figures are shown to remind of the atmosphere at the time, only with some necessary English terms added. The figure numbers are changed. The equations are arranged in nearly the same order as the original ones with some adjustments for convenience of understanding. The equation numbers are changed accordingly.

2.1 Fundamental equations of a system of one degree of freedom

A system of a pump and flow-paths shown in **Fig. 1** is paid attention to. From a large reservoir having a constant surface level, the pump discharges water through a downstream tank having a constant sectional area, *F*, with a constant flow rate Q_d irrespective of the tank water level. It is treated as a system of one degree of freedom. The inertia factor of the system is assumed to be *m*.

If the characteristics of the suction flow-path (pump head – flow-path loss head) is expressed as $f(Q_P)$, the equation of motion for the suction flow-path is given by Eq.(1), and the equation of continuity for the tank is given by Eq.(3).

$$m\frac{dQ_P}{dt} = f\left(Q_P\right) - H \tag{1}$$

$$Q_d = Q_0 = const \tag{2}$$

$$F\frac{dH}{dt} = Q_P - Q_0 \tag{3}$$

Here the inertia factor of the suction flow-path is given as follows;

$$m = \int \frac{dx}{gA} \tag{4}$$

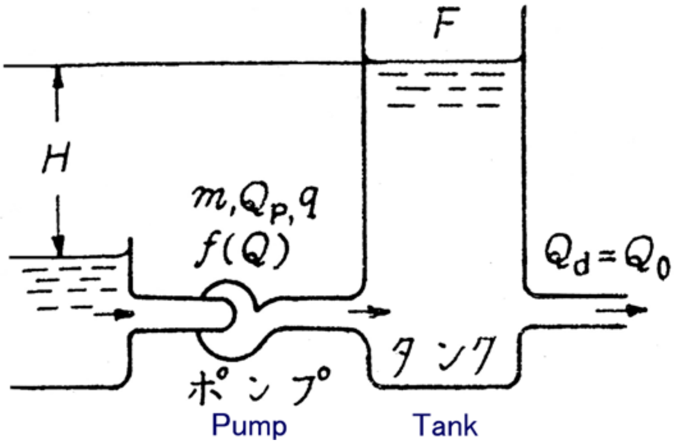

Fig. 1 Pump and flow-path system for description of surging (Fujii [1])

From these equations, when the working condition, defined as the tank water level *H* as the function of pump flow rate Q_p , is expressed as a coordinate of point in the *H*-*Q* plane in **Fig.2**, it is understood that the trajectory of the working point moves in the following manner; In the first place, let us consider the case when, as shown for Q_d (I) in **Fig. 2**, the pump flow rate $Q = Q_p$ is larger than the discharge flow rate from the tank $Q_d = Q_0$, and the water level in the tank is at point A on the characteristic line. In this case, the water supply is surplus, i.e., $Q_p - Q_d > 0$, and the water level in the tank rises as suggested by Eq. (3); at the same time, since $H = f(Q_P)$ at point A, Eq.(1) shows that $dQ_P/dt = 0$, namely, the pump flow rate does not change at this instant. Therefore, at point A, the working point $H = H(Q)$ moves vertically upward as shown by the broken line, where the function $H(Q)$ means the delivery head (tank head) from the suction flow-path as a function of the pump flow rate *Q*, as defined above. When the working point is above the characteristics, i.e., $H > f(Q_P)$, Eq. (1) suggests that $dQ_P/dt < 0$, namely the pump flow rate decreases since the water level in the tank is too high, and the trajectory of the working point turns to the left. When the working point comes to point B with the flow rate Q_d, then $Q_P = Q_d$ and $dH/dt = 0$ from Eq.(3). But, since the water level is still too high, Q_P decreases further, the working point moves horizontally to the left. At point C, the working point moves downward opposite to point A, and at point D the working point moves to the right horizontally opposite to point B. Thus the working point moves counter-clockwise around the equilibrium point. The behavior is similar also when the equilibrium point is in the positive-slope zone of the characteristic curve as for Q_d (II). The situation does not determine the stability itself.

q-equation, surging and relaxation oscillation

For simplicity, a flow disturbance q is set as follows;

$$Q_P - Q_d = q \tag{5}$$

And the characteristic curve is expressed as $f(q)$. Then the following equations are obtained from Eqs. (1) - (3).

$$H + m\frac{dq}{dt} = f(q) \tag{6}$$

$$F\frac{dH}{dt} = q \tag{7}$$

Equation (6) is differentiated by t to become

$$\frac{dH}{dt} + m\frac{d^2q}{dt^2} = \frac{df(q)}{dq}\frac{dq}{dt} \tag{8}$$

Here, the following expression is used.

$$\frac{df(q)}{dq} \equiv a(q) \tag{9}$$

Then Eq. (8) becomes as follows by use of Eq. (7) for dH/dt;

$$m\frac{d^2q}{dt^2} - a(q)\frac{dq}{dt} + \frac{1}{F}q = 0 \tag{10}$$

Equation (10) is a differential equation showing the relation between q and t, i.e., a vibration equation with respect to a displacement equivalent q. Let us name Eq. (10) as ***q*-equation**. In Eq. (10), m is equivalent to a mass, $1/F$ to a spring constant, $-a(q)$ to a resistance coefficient or damping factor, respectively. The resistance equivalent term $-a(q)$ is an inverse-signed slope of the characteristic curve and is to be paid attention to being a function of q.

Since F is the sectional area of the tank, the equivalent spring constant is positive;

$$1/F > 0 \tag{11}$$

Then the system is statically stable with respect q.

As the science of vibration shows, for the situation

$$-a(q)_{q=0} > 0 \tag{12}$$

the vibration in the neighborhood of the equilibrium point is decaying; therefore the working conditions are dynamically stable for all disturbances.

For the condition

$$-a(q)_{q=0} < 0 \tag{13}$$

the amplitude of q grows with time, showing a dynamically unstable condition in the neighborhood of q of zero.

The former case (condition for Eq.(12)) has been frequently treated for problems of hydraulically decaying conditions by assuming, for example,

$$a(q) = \delta|q| \tag{14}$$

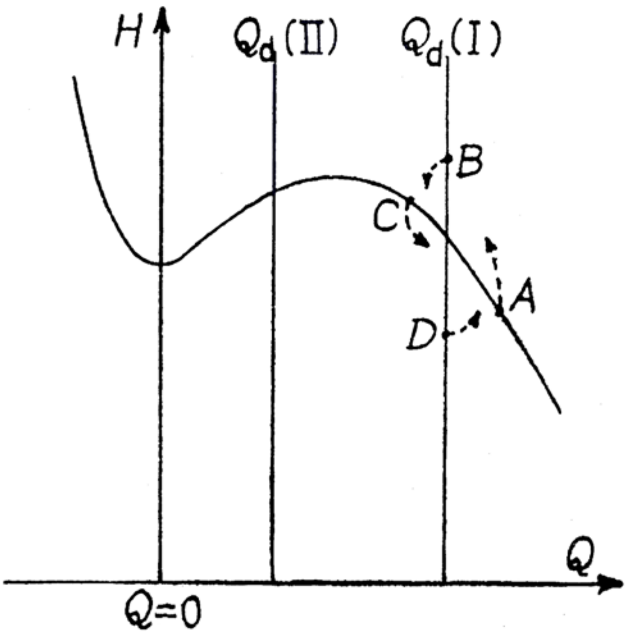

Fig. 2 Pressure-flow characteristics curve of the pump, $H=f(Q_P)$ (Fujii [1])

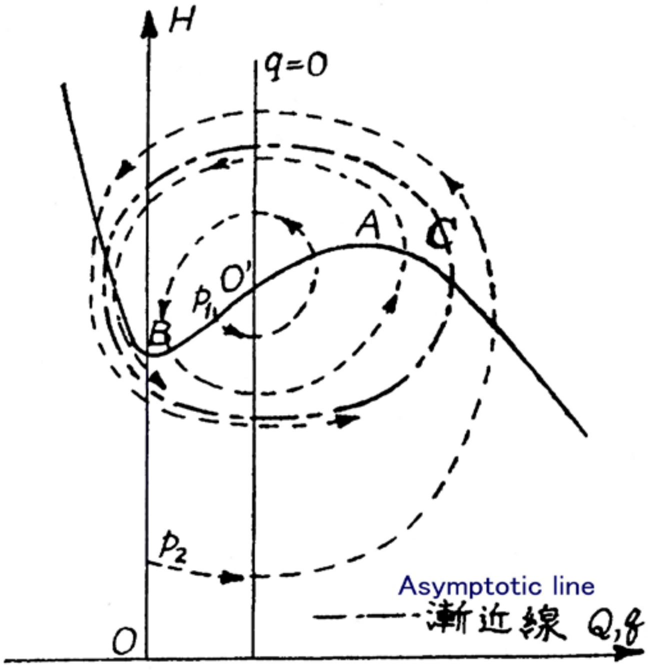

Fig. 3 Surge behaviors on the head-flow plane solved on the basis of Eq.(16) (Fujii [1])

Our problem here concerns the latter condition (condition for Eq.(13)). When Eq. (10) is considered as a system for a pendulum motion (with a mass and a spring) having a degree of freedom, the energy of the system in the neighborhood of the origin will increase with time. The reason is as follows; the increase in the system energy, composed of the kinetic energy of the "mass" and the potential energy of the "spring", during one-cycle period is given by the following;

$$L = \oint \frac{d}{dt}\frac{1}{2}\left(m\dot{q}^2 + \frac{1}{F}q^2 \right) dt = \oint \left(m\ddot{q} + \frac{1}{F}q \right)\dot{q}dt = \oint a(q)\frac{dq}{dt}dq = \oint a(q)\left(\frac{dq}{dt}\right)^2 dt \tag{15}$$

If $a(q)$ is greater than zero, the above integral value becomes always positive for a lapse of time.

In the next place, let us consider a situation of sufficiently large amplitude. As stated above, for sufficiently large values of $|q|$, *a*(*q*) is negative for the case shown in **Fig. 2**, which results in a negative value of the above integral *L*. It means that the oscillation becomes damping. Thus, the oscillation that has grown in the neighborhood of the origin continues the tendency to reach as far as the condition where the integral value *L* become equal to zero, where the oscillation stops growing, changing into a stationary condition of a constant amplitude and a constant cycle period. It is a kind of relaxation oscillation.

H-q equation and trajectories of the working points

Let us examine in further detail the behaviors of the water level *H* and the flow rate *Q* in order to clarify the mechanism of the surging. Equation (7) can be written as follows;

$$F\frac{dH}{dq}\frac{dq}{dt}=q \tag{16}$$

Elimination of *dq/dt* from Eq. (16) by use of Eq.(6) gives the following equation.

$$\frac{dH}{dq}=\frac{1}{\xi}\frac{q}{f(q)-H} \tag{17}$$

Here,

$$\xi\equiv\frac{F}{m} \tag{18}$$

is a parameter, tank sectional area/inertia ratio.

Equation (17) shows the relation between *H* and *q* only, not including the time *t*. Let us name it ***H-q* equation**. By use of the relation, trajectories of surge behaviors can be drawn on the *H-q* plane.

The following case is examined to study the nature of Eq. (17) in the neighborhood of the origin.

$$f(q)=aq \tag{19}$$

Then Eq. (17) becomes as follows;

$$\frac{dH}{dq}=\frac{1}{\xi}\frac{q}{aq-H} \tag{20}$$

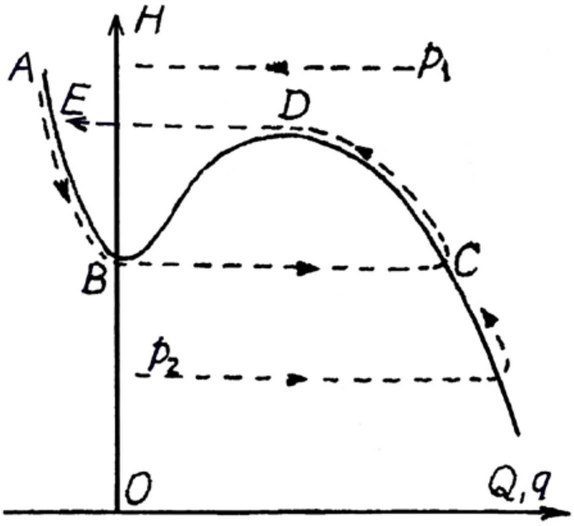

Fig. 4 Surge behavior on the head-flow plane for a limiting condition of near- zero value of *F/m* (Fujii [1])

Approximate behaviors of point (*q*, *H*）specified by Eq. (20) are given as follows;

a = 0: an elliptical trajectory

a > 0:

$\left|\sqrt{\xi}a\right|<2$: a centrifugal trajectory, spiraling counter-clockwise.

$\left|\sqrt{\xi}a\right|>2$: a purely centrifugal behavior results.

a < 0:

$\left|\sqrt{\xi}a\right|<2$: a spiraling centripetal trajectory about the origin.

$\left|\sqrt{\xi}a\right|>2$: a simple centripetal trajectory toward the origin.

Let us return to Eq. (17). If ξ has a finite value, then all the tangential directions of the trajectories are determined for the coordinate on the *H-q* plane by Eq. (17). The trajectories are vertical on the *f*(*Q*) curve because of *dH/dq*→∞, and are horizontal on the line *q* = 0 because of *dH/dq* = 0. If the origin exists in the unstable zone, i.e., between A and B in **Fig. 3**, a trajectory starting from a point $\mathbf{p_1}$ within an asymptotic curve C would approach gradually the C curve, spiraling counter-clockwise and expanding its size, and a trajectory from point $\mathbf{p_2}$ outside of the curve C would approach gradually the C curve, spiraling in the same direction and reducing its size, as seen in **Fig.3**. In either case, they are moving on the C curve, after a lapse of sufficiently long time. It is the steady-state oscillation of the surge. The stationary oscillation cycles exist even in the case of $\left|\sqrt{\xi}a\right|>2$, i.e., non-vibrational instability (divergence instability) in the neighborhood of the equilibrium point.

The situation of sufficiently small ξ is examined. The following transformation of a variable is considered.

$$H'=\sqrt{\xi}H \tag{21}$$

Insertion of the above equation into Eq. (20) gives the following equation.

$$\frac{dH'}{dq}=\frac{q}{\sqrt{\xi}f(q)-H'} \tag{22}$$

Here, if ξ is so small as $\sqrt{\xi}\to0$, or $\sqrt{\xi}f(q)\to0$, then Eq. (22) is transformed to the following equation.

$$\frac{dH'}{dq} = -\frac{q}{H'} \tag{23}$$

Since Eq. (23) expresses an equation of circles, Eq.(20) expresses an equation of ellipses for $\xi \rightarrow 0$. That is to say, if the effects of the inertia term is sufficiently large compared with the tank sectional area, the oscillations could be regarded as harmonic ones, converging into near-elliptical trajectories.

In the case of sufficiently large values of ξ, Eq. (17) demonstrates a most characteristic nature for surge. If ξ is sufficiently large, or the inertia term is sufficiently small, then as far as the denominator $\left[f(q)-H\right]$is finite, or as far as the working point keeps a suitable distance away from the head-flow curve, the right-hand side term of Eq. (17) would be nearly zero; therefore the working point would move nearly horizontally, to the right if below the head curve and to the left if above the head curve (*cf*. **Fig. 4**). When the working point comes near the head curve, $\xi\left\{f(q)-H\right\}$ tends to have a finite value. Near the negative-slope region of the head curve, the trajectory approaches horizontally toward the curve, and then moving nearly along the curve so as to keep the value of $\left[f(q)-H\right]$ to be small. Between B and D in **Fig. 4**, the trajectory leaves the curve horizontally. Finally, the trajectory of the working point or the stationary cycle of the surge is given by C→D→E→B as shown in **Fig. 4**. In the phase D→E and B→C, the flow rate changes rapidly, and it could appear to be a jump for $\xi \rightarrow \infty$. In other words, in the system where the inertia is sufficiently small, the surge cycle is consisted of horizontal tangential lines at the local minimum point and the local maximum point of the head curve and the parts of the head curve in the negative-slope region. The working point moves abruptly from the local maximum point or the local minimum point to the point of the same water level on the other part of the head curve. The sufficiently small inertia convinces the behavior.

The above description is the essence of Fujii [1] translated nearly word-for-word by the authors. It points out the changes in the surge behaviors influenced by the parameter ξ or *F/m*, and the appearance of typical relaxation oscillations at the extremity of the parameter.

Furthermore, Fujii [1] examined the surge phenomena mathematically and has drawn the following conclusions. For the water level to be non-oscillative in the neighborhood of the equilibrium point, it is necessary that Eq. (10) does not have imaginary roots.

$$\frac{a^2}{4m^2} - \frac{1}{mF} > 0 \tag{24}$$

Here, a is the value of $a(q)$ for the equilibrium point.

When the slope of characteristic curve is approximated by

$$a(q) = \alpha - \gamma q^2 \tag{25}$$

then the surge frequency is given by the following equation.

$$\omega^2 = \frac{1}{mF} - \frac{1}{8}\left(\frac{\alpha}{m}\right)^2 \tag{26}$$

In continuation of the above basic discussion, in the second through the fourth reports (Fujii [2-4]), Fujii has extended the discussions about the surge behaviors in more complicated situations, such as pumping systems of a higher degree of freedom, in serial layout, in parallel layout, surge phenomena in long flow-paths where the compressibility effect should be considered, etc.

The second report (Fujii [2]) discussed about the surge behaviors in the system of a higher degree of freedom, for example, several situations where the exit of the above pumping system of a degree of freedom was connected to a reservoir with a constant water level, and where a multitude of pumps and tanks were laid out in series or in parallel. Particularly, Fuiii [2] discussed the case where a parallel operation of two pumps having respective different characteristics, pointing out the resulting drastically complicated surge behaviors possible in the particular system.

Fujii [2] discussed various situations of practical interest such as the differences of the surge behaviors in actual systems of pumps and flow-paths having a higher degree of freedom from those for the pump alone, changes in the stability depending on the layout of the tank and the valve in the system relative to the pump, tendency of surging triggered by occurrence of cavitations, etc. Furthermore, abnormal behaviors in the equilibrium operations in systems of parallel layout, for example, discontinuous shift of working conditions, etc. were discussed. Thus he concluded that almost all phenomena observed or experienced up to the time in surges and hydraulic instabilities in pumping systems had been generally and reasonably explained by these discussions.

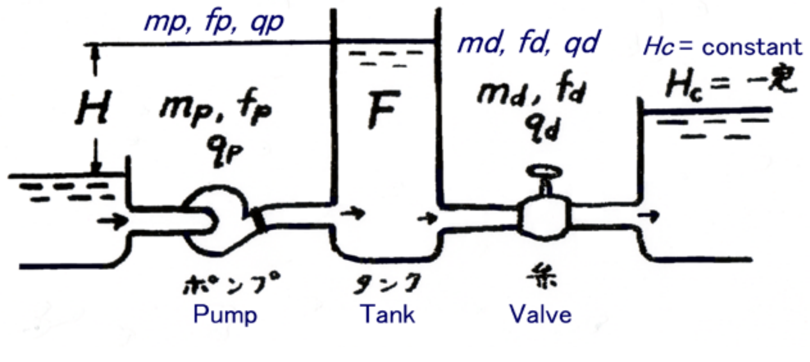

Fig.5 A system of a pump, a tank and flow-paths provided with a valve upstream of an exit reservoir (Fujii [3])

2.2 Basic equations of the system of two-degree of freedom

The third report of Fujii (Fujii [3]) paid attention to the systems of two-degree of freedom, and examined the behaviors of the local flows i.e., in the pump-side flow-path and in the exit valve side flow-path on the *H*-*Q* plane. In the serial flow-path of a low-level reservoir - pump – tank – valve – high-level reservoir, shown in **Fig. 5**, the following basic equations were proposed. Symbols are essentially the same as those employed above. f_P and f_d means the characteristics of the pump system and the valve system, respectively. Subscripts *P* and *d* indicate respectively the pump system flow-path upstream and the downstream resistance flow-path including the valve.

$$H + m_P \frac{dq_P}{dt} = f_P(q_P) \qquad (27)$$

$$H - m_d \frac{dq_d}{dt} = f_d(q_d) \qquad (28)$$

$$F \frac{dH}{dt} = q_P - q_d \qquad (29)$$

The system stability conditions could be examined on the basis of a system of simultaneous equations derived from the above equations (Fujii [3]). The formulation is essentially of the same style as those for the system of compressor and flow-paths proposed by Greitzer [26].

Fuiii [3] discussed the following three examples related with the above situations.

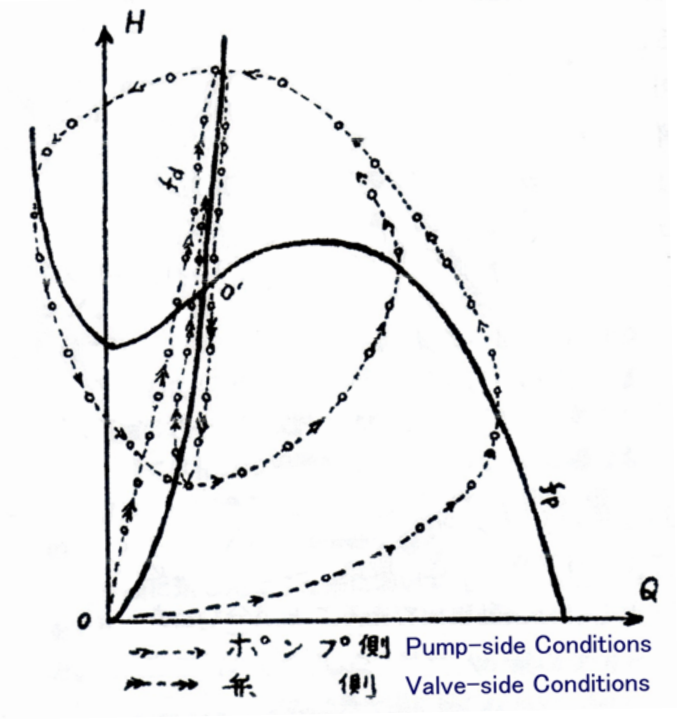

Fig.6 Surge behaviors in the pump-side and in the valve-side for the system of two-degrees of freedom shown in Fig. 5 (Fujii [3])

Example 1 is the case where the tank sectional area is very large and the flow-paths of the pump side and the valve side are relatively short (both inertia factors were sufficiently small). The case depends on the initial condition of the working point, affected by the delivery static pressure and the valve resistance. The pump flow continues to be either in the normal stable condition or in the reversed flow condition.

Example 2 is the case where the valve is throttled sufficiently; the resistance curve passes through the origin of (*Q*, *H*) and crosses the stalled zone of the pump characteristics. **Figure 6** shows the result obtained for some such condition. A surge occurs here. Although the changes in the flow rate in the pump flow-path are significantly large, those in the valve flow-path are extremely small because of the steepness of the valve characteristics. The results can be applied generally for systems where a capacity is located halfway and the exit valve is throttled. The trajectories are given as $H(q_P)$ for the pump-side condition and as $H(q_d)$ for the valve-side one. The significantly large up-and-down of the tank water level in comparison with the height of the pump characteristics curve could be attributed to the relatively large inertia of the pump side flow-path.

In the system of two-degree of freedom, the surge behaviors (**Fig.6**) are different somewhat from those in the ideal system of one-degree of freedom discussed above for a constant discharge flow rate (**Fig. 3**).

Example 3 is the case where the valve port is sufficiently widely opened and the resistance curve passes through the origin, Q=0 and H =0 and crosses the pump characteristics curve in the sound zone having a negative slope. The case converges rapidly to a stable point.

In t**he fourth report (Fujii [4])**, he considered that, with respect to pump surges in a long flow-path without tanks, or surges of compressors or fans in a long pipeline, it is difficult to discuss the system in a divided manner as a finite-degree of freedom one and, at the same time, it could lose the essence of the phenomena. So, Fujii [4] discussed the system as a continuous one, and by applying the equations of waves in consideration of boundary conditions and wave reflections at both ends, showed the characteristic natures of the system, including stability judgment as a continuous system, occurrence of square waves, etc.

It is stated that, although the cause of the surges is not different so much between in the system of finite degree of freedom and in the continuous system, there exists much difference between both with respect to the stability criterion and the surge modes. Therefore, it is necessary to understand essentially the respective natures.

In the situation where a number of pumps, tanks, valves exist halfway in the flow-path system, though exact treatments could be difficult, it could be said very roughly as follows. As a very rough measure, velocity amplitudes tend to be large in the location where the negative resistance exists, and to be small in the location of large resistance, such as valves. Therefore, the surge frequency tends to be not necessarily the lowest natural one of the system in a long flow-path, but could be a higher one if, for example, the pump and the valve are located in close neighborhood.

As can be seen above, Fujii’s reasonings are very basic and plain, but at the same time, thorough and consistent. It could be instructive also to us who tend to stick to details in the present time of high-power computing systems.

As early as 1947, in the extremely confused environments of Japan immediately after the World War II when neither electronic computers nor calculators were available, Fujii clarified completely by his brain by use of only pencils and papers, and possibly slide rules, the mechanism of the surges that had been thought incomprehensible at that time. The results have explained reasonably the various aspects of surge phenomena felt even as “goblin” and could have opened the door to the coming evolution of the turbomachine technology.

3. Evolutions of Surge Researches after Fujii

Surges tend to occur also in the flow-path systems including compressors and fans, affected by the action of the compressibility of the air or the gas playing nearly the same role as the tanks in the pump systems. In Japan the surges appeared to have been keenly interested by engineers and researchers of the fluid-machine-related industries and institutes. Soon after the publication of the Fujii papers ([1-4]), many other research results were published in a rushing manner on the surge phenomena not only in the pump systems but also in the compressor and fan systems. The research results in the period from after Fujii to the 1960’s would be introduced very briefly here. Katto [24] has reviewed them in 1967, regrettably also in Japanese.

(1) The research group led by Kusama [5-9], 1953-1955, conducted theoretical analyses and experimental confirmations on surge phenomena in flow-path systems including centrifugal pumps.

Kusama in the first and the second reports[5] have shown on the basis of detailed analytical examinations that, although the positive-slope characteristics is a necessary condition, the flow-path losses should be taken into account; therefore there could exist situations where no surge occur even in the positive-slope zone.

Kusama, Minami, and Tsuji in the third report [6] conducted experiments on several centrifugal impellers having different values of exit angles, and confirmed the validity of the above theoretical results.

Kusama and other four members in the third report [7] surveyed experimentally the pump working conditions in surge. They observed counter-clock-wise rotations of H-Q loops and changes in the loop sizes depending on the air quantities included in the air tank in the delivery flow-path. They observed no flow reversals within their experimental conditions.

Kusama in the fifth report [8] derived and examined theoretical equations about the stability of serial and parallel operations of pumps. For the serial operations, the results are the same as those for the single pump situations. But in the situation, it is necessary to use a synthetic pump characteristics with the head added together from both pumps for the same flow rate. In the parallel operations, no instabilities could occur when valves are located immediately downstream of respective pumps. But he told that it was too much complicated to draw a general conclusion, in the situation for both valves located downstream of the junction of the exit flow-paths from both pumps.

Kusama, Mizuguchi, and Tsuji in the sixth report [9] showed experimental results on the contents of the fifth report [8]. They have confirmed that the surge occurrence requires to satisfy all the following three conditions, namely, operation in the positive-slope region of the synthetic characteristic curve, existence of air tank in the flow-path, and flow throttling conducted downstream of the air tank. If the synthetic characteristic curve is used, the situation is considered to be the same as that for the single pump situation.

(2) The research group led by Kusama and Tsuji [10-13], 1956-1957, continued the research to extend the surge phenomena in systems of compressors and fans, including theoretical survey and experiments, and development of anti-surge devices.

Kusama, Tsuji, and Oshida in the first report [10] made various measurements, aiming to prevent surges in the systems of centrifugal fans and flow-paths. They conducted synchronous measurements of pressures and flow rates in surges. Effects of lengths of the delivery ducts, fan speeds, etc., on the surge conditions (surge periods, pressure amplitudes, etc.) were surveyed. It was observed that long delivery ducts tended to be affected much by fan rpms, and surge periods tended to be affected by the delivery volumes, etc.

Kusama and Tsuji in the second report [11] paid attention to “two-valve operation method” for surge-prevention. They confirmed experimentally that surges could be prevented by locating two valves in suitable positions in the delivery duct and regulating them properly. They confirmed the results also theoretically.

Tsuji in the third report [12] investigated the features of the two-valve operation method. Two cases were surveyed. The second valve was located at the exit of the delivery duct, and the first valve located either at the inlet of the suction duct or halfway of the delivery duct.

Tsuji, Matsushima, and Terada in the fourth report [13] planned to put the two-valve operation method to practice, and developed a hydraulically-controlled automatic surge-prevention device. They confirmed successful operations of the device on a fan system.

(3) Shimoyama and Ito [14-19], 1957-1960, made various experiments, aiming to clarify surge phenomena in long ducts, i.e., surges in distributed systems.

Shimoyama and Ito in the first report [14] studied on the situations of free oscillations of air columns in duct, resonance frequencies, effects of pipe-end conditions, equivalent lengths of fans, effects of open-end conditions on the damping of the air column oscillations, etc. as the base for studying surges.

Shimoyama and Ito in the second report [15] studied experimentally the oscillating conditions in surge in the flow-path whose delivery duct terminated by a volume. It was found that the oscillation mode was similar to the one in free oscillation. The frequency was lower by 2-10 % than those for the free oscillation. Surge occurred from lower rpms for the larger volume of the duct-end tanks. Surges tend to occur in the basic modes of free oscillations. However, if the flow-path configurations gave large damping to the basic mode, then the surge mode could converge to some higher order mode.

Shimoyama and Ito in the third report [16] studied about the effect of the relative locations of the fan in a duct of constant whole length on the surge. The results were as follows; the velocity oscillation at the fan position depends on a basic mode in the free oscillation condition. The velocity amplitude is one of the important elements for the surge. The surge tends to be violent for the fan located near the oscillation loop (anti-node). On the other hand, the surge could be damped for the fan located near the node. The surge mode could change, depending on the fan flow rate. The surge frequency does not change much by the fan relative position.

Ito in the fourth report [17] tried to prevent or alleviate the occurrence of surges by inserting a valve in the intermediate location of the delivery duct. It showed a possibility to alleviate surges by changing the mode by providing an additional volume at a suitable location and by absorbing the oscillation energy by providing a valve. They obtained experimentally materials effective for the optimizations.

Ito in the fifth report [18] studied about the surges in a system of serial operation of two fans. The surge mode was also determined by one of the basic modes determined by the duct length and the end conditions. It could not be determined only by the synthetic pressure-flow characteristics. This situation should take into consideration of both conditions of the locations and the characteristics of respective fans. For both of the fans locations near the position of the basic mode loop, the surge corresponding to the mode tend to be violent

Ito in the sixth report [19] made considerations about the surge modes in ducts. With respect to the condition of the sustainability of the oscillations, he formulated approximate equations and examined it theoretically, and confirmed the results experimentally. It was found out that the air column oscillation in surges tends to select one of the lower or medium orders of the basic modes, which finally become predominant.

(4) Katto [20, 21], 1960, studied the surge behaviors in the system with a low-pressure axial flow fan mounted at the inlet of the duct as resonant surge phenomena. He conducted detailed measurements of the characteristics of the fan and the ducts. On the bases of the experimental data, he evaluated equivalent capacities and equivalent inertias for construction of equivalent electrical circuits. The behaviors evaluated by use of the equivalent circuits are in good coincidences with the measured surge behaviors. He studied experimentally the effects of the duct lengths and of changes in the relative locations of in-pipe orifices on the surge. He observed that surges of either the first mode or the second mode could occur, depending on the location of the orifice.

He pointed out additionally as follows; in the conventional surge analyses, the throttling elements such as orifices and valves, etc., are considered to be related to the surge behaviors through the resistance characteristics. However, in some particular circumstances, the throttling elements could be accompanied by some capacitance action, which could thus mean a loss of the primary significance as the flow-resistance characteristics.

(5) Takeya [22, 23], 1961, tried to predict the surge phenomena of a multi-stage axial flow compressor.

Takeya in the first report [22] formulated a system of equations for approximating the compressor made up of three blocks of subcomressors and combining the respective equivalent electrical circuits representing them. At the same time, he formulated a distributed system consisting of one-dimensional equations of motion and continuity, and boundary conditions. He applied both methods to the compressor to evaluate surge points of the compressor. He obtained nearly coincident surge points for both procedures.

Takeya in the second report [23] studied the surge behaviors for changing speeds in the compressor approximated by two-divided parts and represented by equivalent electrical circuits, assuming non-dimensional stage characteristics. The results showed that the surge behaviors were affected by both of the electric resistance terms R_1 and R_2 for the frontal part and the rear part, respectively. The resistance term is corresponding to the stage characteristic slope, with a negative resistance value indicating a positive characteristic slope, vice versa. The analyses for changes in the compressor speeds showed that surging occurred in distinctive three regions in large; (1) for R_1 having some negative near-zero values in positive R_2 situations, (2) for R_2 having some negative near-zero values in positive R_1 situations, and (3) some near-zero values of $R_1 + R_2$, or an averaged characteristic slope of the whole stages. The respective situations are considered to correspond to the surges for compressor conditions of lower speeds, higher speeds and medium speeds. In other words, they are similar to actual surging conditions caused respectively by front-stage stalling for lower speeds, rear-stage stalling for higher speeds, and whole-stage approaching to stalling for near-design speeds. The results showed the effects of stage mismatchings on the surge of a multi-stage compressor, depending on the changes in the compressor speeds.

Katto [24] made a review concerning these researches in Japan in 1967.

A book “Dynamics for a Million People” [25] published in 1969 explains plainly the up-to-date knowledge of vibrations and oscillations in the wide area of mechanical engineering including fluid machines and surge phenomena.

Thus, the clarification of the principle of surges in pumping systems initiated by Fujii[1-4] had been pushed forward to further stages of theoretical verification and experimental confirmation, extension to compressor and fan systems, development of anti-surge devices, etc., by the efforts of many Japanese researchers in the period. The authors believe that their efforts must have contributed much toward the establishment of the whole view of surge phenomena in the world.

4. Additional Notes

In 1976, Greitzer [26, 27] made a great step in the field of compressor surge phenomena. The Greitzer’s researches, whose relationships with those of Fujii [1-4] are not clear, are seen to have nearly the same style of formulation as Fujii [1-4] and to have advanced further the Fujii’s results in a sense.

Fujii [1-4] has found out the principle of the surge as the self-excited unstable flow oscillation, and made clear the various situations of the phenomena widely and comprehensively. On the other hand, Greitzer [26, 27], focusing on the compressor surge phenomena more quantitatively and precisely, has come closer to the whole view of the phenomena. He has achieved the researches by employing dimensionless expressions, proposing a dominating non-dimensional parameter of generality, i.e., B

parameter, surveying the detailed effects of the B parameter on the surge behaviors, showing the existence of stall stagnation boundaries determined by a threshold value of B parameter. At the same time, he conducted experimental confirmations of the analyzed results. It is well-known that the Greitzer's energetic activities since then add much to the sciences and practices in the extensive fields including stalls and surges of compressors.

Here we would like to show the common line of thinking between Greitzer and Fujii, for reference.

For the system shown in **Fig.5** where the delivery flow-path is terminated by a valve, basic equations for the analysis of pump operations given by Fujii [3] are fundamentally of the same style as for the compressor system given by Greitzer [26, 27]. The situations are outlined as follows (Tsujimoto [28]).

The suction flow-path is represented by the length L and the sectional area A, then the inertia factor is given by the following equation.

$$m = L/gA \tag{29}$$

The apparent elasticity of the delivery tank is

$$K = F/(\rho g A) \tag{30}$$

Then the resonant frequency based on the fluid mass in the suction flow-path and the tank elasticity is given by the following equation;

$$\omega = \frac{1}{\sqrt{\rho L K}} \tag{31}$$

Normalization is conducted by use of the pump peripheral speed U and the representative time ($1/\omega$);

$$Q = AU\phi \tag{32}$$

$$f_P = (U^2/2g)\psi_P \tag{33}$$

$$H = (U^2/2g)\psi_T \tag{34}$$

$$t = \sqrt{\rho L K}\,\tau \tag{35}$$

Here, φ: flow coefficient, ψ_P : pump pressure coefficient, ψ_T : coefficient giving the tank water level, τ: non-dimensional time.

The following equation is derived from Eq.(26).

$$\frac{d\phi_P}{d\tau} = B_P(\psi_P - \psi_T) \quad , \tag{36}$$

Here,

$$B_P = \frac{U}{2}\sqrt{\frac{\rho K}{L}} \tag{37}$$

B_P is a dimensionless factor in the pump system equivalent to Greitzer's B parameter. A similar normalization of Eq. (28) gives the following equation.

$$\frac{d\psi_T}{d\tau} = \left(\frac{1}{B_P}\right)(\phi_P - \phi_d) \tag{38}$$

The following formula is obtained similarly to Eq. (19) from Eqs. (36) and (38).

$$\frac{d\psi_T}{d\phi_P} = \left(\frac{1}{B_P{}^2}\right)\left(\frac{\phi_P - \phi_d}{\psi_P - \psi_T}\right) \tag{39}$$

In the system of a compressor and flow-path with a downstream plenum of volume V, the apparent elasticity is given as follows by use of the speed of sound a and under the assumption of isentropic changes;

$$K = V/(\rho A a^2) \tag{40}$$

B and B_P parameters are expressed more concretely in terms of the above variables;

For compressors and fans (Greitzer [26]);

$$B = \frac{U}{2a}\sqrt{\frac{V}{AL}} \tag{41}$$

For pumps (Tsujimoto [28]);

$$B_P = \frac{U}{2}\sqrt{\frac{F}{gAL}} \tag{42}$$

The above normalization of the equations and parameters could make possible to understand more commonly the surge phenomena in both of the pump system and the compressor or fan system.

Fujii [1-4] discussed the surge behaviors in terms of the parameter $\xi = F/m$, which is related with the equivalent B_P parameter by the following relationship.

$$\xi = \left(\frac{2gA}{U}\right)^2 {B_P}^2 \tag{43}$$

5. Postwords

This paper introduced briefly two decades of surge researches in Japan, showing a translated essential part of Fujii's research on the mechanism of pump surges in 1947 and abstracts of successively conducted researches in Japan up to 1960's.

The subsequent developments in the researches on the stability of pumping systems can be found in the comprehensive review by Greitzer [29], which includes a very wide range of recent topics such as rotating stalls, stall stagnations, effects of casing treatments, effects of inlet distortions, cavitation-induced instabilities, etc.

Katto [24] reviewed the research history in Japan in 1967 and expressed his feeling as follows; "It is very interesting that the essence and the various aspects of the surge phenomena can be explained convincingly in a unified manner on the basis of a fundamental principle. The history of the researches emphasizes that precise recognitions of the phenomena and thorough pursuits of the problems have been the key to the success in clarification of the unknown phenomena." It must have been a dramatic scene of an emerging technological breakthrough. At the same time, even in the present time of high-power computing systems, we can learn much from the attitudes toward the phenomena in the pioneering papers, i.e., watching and thinking basically.

The present authors would be happy if this introduction could be helpful for the people concerned and interested in the surge phenomena of turbomachines.

Nomenclature

a	Slope of pump characteristics	q	Flow rate disturbance
	Speeed of sound	t	time
A	Sectional area of compressor suction	U	Compressor reference blade speed
	duct	x	Flow-path coordinate in the flow direction
B	Greitzer's B parameter	α	Linear term approximation of the
B_P	Equivalent B parameter in pump		characteristics slope
	systems	γ	Third term approximation of the
F	Sectional area of delivery tank in		characteristics slope
	a pump system	φ	Non-dimensional flow rate
f	Pump head as a function of flow	ξ	Fujii's parameter of tank sectional area/
g	Gravitational constant		flow-path inertia factor
H	Surface level of water in the	ρ	Flow density
	delivery tank	ψ	Non-dimensional pressure
K	Apparent elasticity	ω	Surge cycle frequency
L	Length of compressor suction duct	Subscript	
m	Ineratia factor of the flow-path	P	Pump-side flow-path
Q	Flow rate	d	Delivery-side flow-path

References

[1] Fujii, S., 1947, Stability and Surge of Centrifugal Pump and Flow-path Systems, The 1-st Report (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 13, No. 44, pp. 184-191

[2] Fujii, S., 1947, Stability and Surge of Centrifugal Pump and Flow-path Systems, The 2-nd Report (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 13, No. 44, pp. 192-201

[3] Fujii, S., 1948, Stability and Surge of Centrifugal Pump and Flow-path Systems, The 3-rd Report (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 14, No. 48, pp. 12-17

[4] Fujii, S., 1948, Stability and Surge of Centrifugal Pump and Flow-path Systems, The 4-th Report (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 14, No. 48, pp. 17-25

[5] Kusama, H., 1953, Study on Surging of Centrifugal Pumps, The 1-st and 2-nd Reports; Stability of Pumping System (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 19, No. 85(3), pp. 43-49

[6] Kusama, H., Minami, S., and Tsuji, S., 1954, Study on Surging of Centrifugal Pumps, The 3-rd Report (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 20, No. 89, pp. 16-19

[7] Kusama, H., Tsuji, S., 1954, Study on Surging of Centrifugal Pumps, The 4-th Report; On the running conditions of pump when the system falls in surging (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 20, No. 93, pp. 325-329

[8] Kusama, H., 1955, Study on Surging of Centrifugal Pumps, The 5-th Report; Stability of Series and Parallel Running (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 21, No. 105(3), pp. 350-355

[9] Kusama, H., Tsuji, S., and Oshida, Y., 1955, Study on Surging of Centrifugal Pumps, The 6-th Report; Experimental Study of

Series and Parallel Running, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 21, No. 105(3), pp. 355-358
[10] Kusama, H., Tsuji, S., and Oshida, Y., 1956, Study on Surging of Fans, The 1-st Report, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 22, No. 117(3), pp. 360-364
[11] Kusama, H., and Tsuji, S., 1956, Study on Surging of Fans, The 2-nd Report, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 22, No. 121(3), pp. 642-648
[12] Tsuji, S., 1957, Study on Surging of Fans, The 3-rd Report, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 23, No. 133(3), pp. 628-633
[13] Tsuji, S., Matsushima M., and Terada, S., 1957, Study on Surging of Fans, The 4-th Report; Surge Preventive Device (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 23, No. 133(3), pp. 628-633
[14] Shimoyama, Y., and Ito, T., 1957, Experiments on the Surging of a Blower, The 1-st Report; Free Vibration of Air Columns, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 23, No. 125(3), pp. 25-31
[15] Shimoyama, Y., and Ito, T., 1957, Experiments on the Surging of a Blower, The 2-nd Report, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 23, No. 125(3), pp. 32-37
[16] Shimoyama, Y., and Ito, T., 1957, Experiments on the Surging of a Blower, The 3-rd Report, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol .23, No. 125(3), pp. 38-44
[17] Ito, T., 1960, Experiments on the Surging of a Blower, The 4-th Report; An Approximate Determination of the Amplitudes of the Surging and an Experiment on the Prevention of the Surging, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 26, No. 162(3), pp. 274-283
[18] Ito, T., 1960, Experiments on the Surging of a Blower, The 5-th Report; The Surging in Series Running of Blowers, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 26,No. 162(3), pp. 283-288
[19] Ito, T., 1960, Experiments on the Surging of a Blower, The 6-th Report; A Consideration on the Types of the Surging, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 26,No. 162(3), pp. 289-299
[20] Katto, Y., 1960, Some fundamental Nature of Resonant Surge, The 1-st Report; Experimental Results and Analysis of Oscillating Systems, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 26, No. 162(2), pp. 256-264
[21] Katto, Y., 1960, Some fundamental Nature of Resonant Surge, The 2-nd Report; Theoretical Analysis, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 26, No. 162(2), pp. 265-273
[22] Takeya, K., 1961, Studies on the Limits of Surging in in Multi-Stage Axial-Flow Compressors, The 1-st Report; Methods for Calculating the Surging Points, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 27, No. 183, pp. 1801-1808
[23] Takeya, K., 1961, Studies on the Limits of Surging in in Multi-Stage Axial-Flow Compressors, The 2-nd Report; The Surging Characteristics, (in Japanese), Transaction of Japan Society of Mechanical Engineers, Vol. 27, No. 183, pp. 1809-1816
[24] Katto, Y., 1967, A Review on the Principle and Various Phenomena in Surges of Turbomachines, (in Japanese), “Science of Machines”, Yokendo Publishing Company, Japan, Vol. 69, No. 1, pp. 208-214
[25] Noguchi, S., and Kitasato, K. (Editors), “ Dynamics for a Million People”, Published by AGNE Publishing Company, Japan, (1969-5), p.324. Chapter 12, God of Winds and Human Lungs (on the Vibrations of Fans and Compressors), (in Japanese), written by Oyama, Iwao
[26] Greitzer, E.M., 1976, Surge and Rotating Stall in Axial Flow Compressors, Part I: Theoretical Compression System Model, ASME, Journal of Engineering for Power, Vol. 98, pp. 190-198
[27] Greitzer, E.M., 1976, Surge and Rotating Stall in Axial Flow Compressors, Part II: Experimental Results and Comparison with Theory, ASME, Journal of Engineering for Power, Vol. 98, pp. 199-217
[28] Tsujimoto, Y., 1998, Instability Phenomena in Turbomachinery, (in Japanese), (Additional Chapter 11 in Japanese Translated Edition of “ Brennen, C. E., Hydrodynamics Pumps” , translated by Tsujimoto, Y.), Osaka University Press, (1998-3), pp.302-308
[29] Greitzer, E.M., 1982, The Stability of Pumping Systems-The 1980Freeman Scholar Lecture, Journal of Fluids Engineering, ASME, Vol. 103, pp. 193-242

Nobuyuki Yamaguchi Meisei University (1994-2011, now retired, Professor Emeritus), Tokyo, Japan. Field of activity: aerodynamics of axial flow compressors and fans, fluid mechanics and engineering in industrial systems. R and D engineer (1965-1994) at Takasago Research and Development Center, Mitsubishi Heavy Industries, engaged in R and D of axial flow compressors and fans for industrial use and gas turbines. BA (1963), MA (1965) and Dr. Eng. (1978) from Tokyo University

Yoshinobu Tsujimoto Osaka University (1977-2013, now retired, Professor Emeritus), Osaka, Japan
Field of Activity; Unsteady problems in turbomachinery, cavitation, rotor dynamics, BA(1971), MA(1973), and Dr. Eng. (1977) from Osaka University