Experimental Study of Static Characteristics of Wall-Reattachment Fluidic Amplifiers*

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In this investigation, the input characteristics of wall-reattachment fluidic amplifiers are determined by using differential quantities between the left and right sides of the amplifiers, i.e., the differential control flow Δq_c , the differential control pressure Δp_c and the differential output flow ΔQ . The functional form of the characteristic is approximately expressed as follows: $\Delta q_c/Q_s = F[\Delta p_c/P_s - K_1(\Delta Q/Q_s)] + K_2(\Delta Q/Q_s)$. On the basis of the above equation, the momentum equations and the equation of continuity for the flow in the interaction region of the amplifier, the respective pressure and flow at each of the two control ports and the output ports are theoretically calculated, and also an equation of the output characteristic expressed by differential quantities is theoretically derived. The validity of theoretical results is confirmed experimentally.

1. Introduction

The exact input and output characteristics of wall-reattachment fluidic amplifiers should be expressed as the relation among eight variables consisting of the pressures and the flows at the control and output ports. However, it is very difficult to derive amplifier characteristics in such a general form. Therefore, several works in the past have represented the input characteristic as a relation between the pressure and the flow at one side of the control ports under the condition that the opposite control port is blocked or open to the ambient. But such an expression for the input characteristics is inconvenient to deal analytically with the cases when both control ports are active (for example, sonic oscillators, feedback oscillators, etc.). On the other hand, it has been already pointed out that the characteristics of amplifiers can be simply expressed by using pressure differences and flow differences at the left and right sides of the amplifier.

This study experimentally indicates that the differential expression of the input characteristics of the amplifiers including the effect of the output loading can be applied over a wide range of operating conditions, and that all of eight variables, i.e., the pressures and the flows at the left and right control ports and output ports in the interaction region of amplifiers, can be obtained by simultaneously solving the input characteristics,

equations of momentum balance for a control volume, an equation of continuity and equations for output conditions. Furthermore, it is shown that a formula for the output characteristics can be derived from the equations cited above. Theoretically inferred facts are confirmed experimentally.

2. Nomenclature

- A : cross-sectional area of output channel
- K, K_1 , K_2 : constant coefficients
- L_s : splitter distance
- P_i : left and right output pressures at interaction region ($i = 1, 2$)
- P_o : ambient pressure
- P_n : pressure at exit of power nozzle
- P_s : kinetic pressure in power nozzle
- P_{ci} : pressures at left and right exits of control ports ($i = 1, 2$)
- P_{cr} : control pressure difference at switching
- Q_i : left and right output flow ($i = 1, 2$)
- Q_s : power jet supply flow
- q_{ci} : left and right control flow ($i = 1, 2$)
- q_{cr} : control flow difference at switching
- q_t : total inflow from control ports
- R_o : resistance of output ports
- r_c : resistance of control ports
- S : cross-sectional area of control ports
- S_n : cross-sectional area of power nozzle
- w_c : control port width
- w_n : power nozzle width
- α : angle of inclination of reattachment wall
- ρ : density of working fluid

Subscripts

- $i = 1, 2$: represent left and right, respectively

Fig. 1 shows a sketch of the wall-

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Fig. 1 Sketch of amplifier and notation

reattachment amplifier and the main notation used in this paper.

3. Tested amplifiers and experimental setup

Fig. 2(a) and (b) show geometries and dimension of the tested amplifiers which are fabricated symmetrically. The depth is 12 mm, the splitter distance is adjustable in the range of 5~60 mm and the offset is 0 for the amplifier A and 1.9 for the amplifier B. Both amplifiers have no vent in order to prevent a complicated flow.

Fig. 3 shows a general layout of the experimental setup to measure the static characteristics of the amplifiers. Water is the working fluid in all experiments, and the tested amplifiers are submerged in a water tank. The left control flow q_{c1} is adjusted by the valve A and the right control flow q_{c2} is adjusted by the valve B with the valve C closed when $q_{c2} > 0$. However, when $q_{c2} < 0$ the valve B is closed and the valve C is open, in order to connect the right control port and the water jet pump which sucks the flow from the am-

Fig. 3 Layout of experimental setup

plifier. The sucked control flow is adjusted by the valve C.

The power jet flow, the output flows and a relatively large amount of control flows are measured by area flowmeters. For a small control flow, capillary flowmeters are used. The control and output pressures are measured by water-column manometers. As the resistance of the control nozzles is very small, the pressure at the control plenum chamber p_{ci} is measured as a substitute for the pressure at the control nozzle exit p_{ci} .

4. Input characteristics

The differential input characteristics, i.e., the relation between the control pressures difference $\Delta p_c = p_{c1} - p_{c2}$ and the control flow difference $\Delta q_c = (q_{c1} - q_{c2})/2$, are experimentally measured under the following conditions.

- (1) The power jet flow Q_s is constant.
- (2) The output flow Q_1 and Q_2 are equalized.
- (3) The flow into the left control port is equal to the outflow from the right control port, i.e., $q_{c1} = -q_{c2}$.

Fig. 4(a) and (b) show some typical input characteristics measured for the amplifiers A and B. The abscissa and the ordinate represent the normalized pressure difference $\Delta p_c/P_s$ and the normalized control flow difference $\Delta q_c/Q_s$, respectively, where Q_s is the power jet flow and P_s is the kinetic pressure in the power nozzle ($= \rho Q_s^2 / 2S_n^2$). As already reported, the normalized input characteristic curve has the same form irrespective of the power jet flow Q_s .

4.1 Effects of splitter distance Fig. 4(a) and (b) show systematic changes of the input characteristics of the amplifiers A and B with a change of the splitter distance L_s/w_n .

In the case of a small offset shown in Fig. 4(a), for small L_s/w_n , the input characteristic curve takes a monotonously increasing shape of the third order, and in this case, the amplifier does not give

Fig. 2 Geometries and dimensions of tested amplifiers

bistability. Hereafter, this sort of characteristic curve is referred to as a curve of 'type I'. On the other hand, for large L_s/w_n , the characteristic curves take the shape N, which has a maximum and a minimum point corresponding to the switching points. The curves lack measured values between the maximum and the minimum because of flow instability. The left and right branches of the curves correspond to the states where the power jet reattaches to the left and right side walls, respectively. In this case, the amplifiers become bistable. Hereafter, this sort of curve is referred to as 'type II'.

In the case of the large offset amplifier B shown in Fig. 4(b), for small L_s/w_n , the input characteristic curve separates into three branches. The left, the middle and the right branches correspond to the flows reattaching to the left wall, to the splitter and to the right wall, respectively. Also in this case, there is no measured value available for these branches. This sort of characteristic curve is hereafter referred to as a 'type III' curve. For large L_s/w_n , the characteristic curve becomes a type II in the same manner as the small offset amplifier A.

As previously mentioned, the portion lacking measured values in the characteristic curve was attributed to flow instability. Taking into consideration that

(a) Offset=0

Amplifier A

(b) Offset=19wn

Amplifier B

Fig. 4 Effect of splitter distance and offset on input characteristics

the origin of the curve, i.e., $p=0, q=0$, corresponds to a symmetrical flow under a symmetrical boundary condition, the characteristic curve for the unstable portion is presumed to be represented by a curve passing through the origin and the switching points of each branch of the curve. In this study, the curve for the unstable portion is approximated by a straight line passing through the three points as shown in Fig. 4 (broken lines). The input characteristics have a negative resistance in this portion.

4.2 Effects of output loading In order to determine the effects of output loading, the input characteristics for various values of the output flow difference $\Delta Q = Q_1 - Q_2$ are measured, where a condition for the control flow $q_{c1} = -q_{c2}$ is imposed. The results are shown in Fig. 5, in which the characteristic curves are plotted for the parameter ΔQ and the switching points of each curve are connected by broken lines.

As seen from Fig. 5, each input characteristic curve for $\Delta Q \neq 0$ has almost the same form as the curve for $\Delta Q = 0$, and it

(a) Offset=0

Amplifier A

(b) Offset=19wn

Amplifier B

Fig. 5 Effect of output flow on input characteristics

moves in the right upper direction with an increasing ΔQ . Fig. 6 indicates measured values of the horizontal and the vertical shifts p_0 and q_0 of the input curves with the increase of ΔQ . The results indicate that p_0 and q_0 are proportional to ΔQ . Therefore, p_0 and q_0 can be approximated by the following expressions.

$$p_0/P_s = K_1(\Delta Q/Q_s), \quad q_0/Q_s = K_2(\Delta Q/Q_s) \dots (1)$$

where K_1 and K_2 are the slopes of the straight line in Fig. 6 and represent influencing factors of the output loading.

From the arguments so far, it is concluded that the input characteristics of the amplifiers can be approximately formulated as follows:

$$\Delta q_c/Q_s = F[\Delta p_c/P_s - K_1(\Delta Q/Q_s)] + K_2(\Delta Q/Q_s) \dots (2)$$

where

$$\left. \begin{aligned} \Delta p_c &= p_{c1} - p_{c2}, \quad \Delta q_c = (q_{c1} - q_{c2})/2 \\ \Delta Q &= Q_1 - Q_2 \end{aligned} \right\} \dots (3)$$

and $F(\Delta p_c/P_s)$ is the input characteristic function for $\Delta Q = 0$.

The influencing factors of the output loading K_1 and K_2 gradually decrease with an increase of the splitter distance and ultimately vanish for L_s/w_n above a certain critical value. The fact implies that the amplifier becomes insensitive to output loads when L_s/w_n is larger than the critical value. In order to examine the degree of the output load effects on the input characteristics, a switching flow q_{cr1} in the case of the left output port blocked is compared with a switching flow q_{cr2} in the case of the right output port blocked, where q_{cr1} and q_{cr2} indicate the control flow difference at which the power jet switches from the left to the right side. Fig. 7 shows the measured q_{cr1} (●) and q_{cr2} (○) as a function of L_s/w_n . q_{cr1} and q_{cr2} are to some extent different for small L_s/w_n , but they coincide in the range of $L_s/w_n > 14$ for the amplifier A and in the range $L_s/w_n > 25$ for the amplifier B.

Fig. 6 Parallel shifts p_0 and q_0

That is, the amplifiers A and B become load-insensitive for $L_s/w_n > 14$ and for $L_s/w_n > 25$, respectively.

4.3 Effects of the total inflow from the control ports So far, the measurements of the input characteristics are carried out under the constraint condition $q_{c1} = -q_{c2}$, or $q_{c1} + q_{c2} = 0$. But in general, the amplifier is not always operated under this condition. Thus, the input characteristics for the case $q_{c1} \neq -q_{c2}$ must be investigated. In the present study, the total inflow from both control ports into the interaction region is defined as $q_t = q_{c1} + q_{c2}$, and the effects of q_t on the input characteristics are examined experimentally.

Fig. 8 indicates the input curves for various values of q_t and for $q_{c2} = 0$, i.e., with the right control port blocked. As a result, it is confirmed that the input curves do not change in form for the total inflow range from about $4q_{cr}$ to $-4q_{cr}$. Of course, the curve for $q_{c2} = 0$ coincides with the curve of constant q_t . Furthermore, the switching pressure p_{cr}/P_s and the switching flow q_{cr}/Q_s are shown as functions of q_t in Fig. 9. As seen from the figures, p_{cr}/P_s and q_{cr}/Q_s can be regarded as constant for $|q_t/Q_s| < 0.05$.

5. Input characteristics on one side

Since the input characteristic equation (2) (which is referred to as $\Delta p_c - \Delta q_c$

Fig. 7 Switching flow rate as a function of splitter distance
L.S = Load-sensitive
L.I = Load-insensitive

characteristics hereafter) is expressed only by differential quantities between the left and right sides of the amplifier, it is necessary to derive other equations related to the flow in the interaction region in order to obtain individual quantities p_{ci} , q_{ci} , P_i and Q_i ($i = 1, 2$) and the input characteristics on one side, i.e., $p_{c1} \sim q_{c2}$ characteristics.

First, two momentum balance equations are derived by applying momentum theory to a control volume chosen in Fig. 1. Eq. (4) is an equation of the control flow direction (x-direction) and Eq. (5) one of the power jet direction (y-direction).

$$-F_x(p_{c1} - p_{c2}) - (A \sin \alpha)(P_1 - P_2) = \left(\frac{\rho \sin \alpha}{A} \right) (Q_1^2 - Q_2^2) + \frac{\rho}{S} (q_{c1}^2 - q_{c2}^2) \quad (4)$$

$$F_y(p_{c1} + p_{c2}) - (A \cos \alpha)(P_1 + P_2) + S_n P_n = \left(\frac{\rho \cos \alpha}{A} \right) (Q_1^2 + Q_2^2) - \frac{\rho}{S_n} Q_s^2 \quad (5)$$

where P_x and P_y are the x and y components of the force exerted by the amplifier wall on the fluid, and they are assumed to be $P_x = F_x(p_{c1} - p_{c2})$ and $P_y = F_y(p_{c1} + p_{c2})$, in which F_x and F_y can be regarded as approximately constant (refer to Appendix 2).

Second, the equation of continuity for the control volume is

$$Q_1 + Q_2 = Q_s + q_{c1} + q_{c2} \quad (6)$$

Fig. 8 Effect of total inflow on input characteristics

Fig. 9 Relation of switching flow and pressure to total inflow

Third, the characteristics of output load are

$$P_1 - P_0 = R_0 Q_1, \quad P_2 - P_0 = R_0 Q_2 \quad (7)$$

where R_0 is the resistance of the output ports and P_0 the ambient pressure.

Eq. (2)~Eq. (7) are normalized as follows:

$$\left. \begin{aligned} \Delta \bar{q}_c &= F(\Delta \bar{p}_c - K_1 \Delta \bar{Q}) + K_2 \Delta \bar{Q}, \quad \Delta \bar{p}_c = \bar{p}_{c1} - \bar{p}_{c2} \\ \Delta \bar{q}_c &= (\bar{q}_{c1} - \bar{q}_{c2})/2, \quad \Delta \bar{Q} = \bar{Q}_1 - \bar{Q}_2 \\ d_1 \Delta \bar{p}_c + d_2 (\bar{P}_1 - \bar{P}_2) + d_3 (\bar{Q}_1 + \bar{Q}_2) \Delta \bar{Q} \\ &+ 2d_4 \bar{Q}_1 \Delta \bar{q}_c = 0 \\ -d_5 (\bar{p}_{c1} + \bar{p}_{c2}) + d_6 (\bar{P}_1 + \bar{P}_2) + d_7 (\bar{Q}_1^2 + \bar{Q}_2^2) &= d_8 \\ \bar{Q}_1 + \bar{Q}_2 &= \bar{q}_t + 1, \\ \bar{P}_1 &= R_0 \bar{Q}_1, \quad \bar{P}_2 = R_0 \bar{Q}_2, \quad \bar{q}_t = \bar{q}_{c1} + \bar{q}_{c2} \end{aligned} \right\} \quad (8)$$

where

$$\begin{aligned} \bar{p}_{ci} &= p_{ci}/P_s, \quad \bar{q}_{ci} = q_{ci}/Q_s, \quad \bar{P}_i = P_i/P_s \\ \bar{Q}_i &= Q_i/Q_s \quad (i=1, 2), \quad \Delta \bar{p}_c = \Delta p_c/P_s \\ \Delta \bar{q}_c &= \Delta q_c/Q_s, \quad \Delta \bar{Q} = \Delta Q/Q_s, \quad \bar{q}_t = q_t/Q_s \\ d_1 &= 1, \quad d_2 = A \sin \alpha / F_x, \quad d_3 = \rho Q_s^2 \sin \alpha / (F_x P_s S) \\ d_4 &= \rho Q_s^2 / (S F_x P_s), \quad d_5 = 1, \quad d_6 = A \cos \alpha / F_y \\ d_7 &= \rho Q_s^2 \cos \alpha / (F_y P_s S) \\ d_8 &= (\rho Q_s^2 + S_n^2 P_n) / (F_y S_n P_s), \quad R = Q_s R_0 / P_s \end{aligned}$$

Twelve variables, p_{ci} , q_{ci} , P_i , Q_i ($i = 1, 2$), p_c , q_c , ΔQ , and q_t involved in Eq. (8) can be simultaneously solved from 10 equations in Eq. (8) and two input conditions appropriately given.

Fig. 10 (a) shows the input characteristics on one side (referred to as $p_{c1} \sim q_{c1}$ characteristics hereafter) calculated from

(a) Theoretical results

(b) Experimental results

Fig. 10 Input characteristics on one side ($q_t = \text{constant}$)

Eq. (8) for constant q_t . In the calculation, the differential input characteristic function $F(\Delta p_c/P_s)$ shown in Fig. 8 is used. The broken lines in each $p_{c1} \sim q_{c1}$ curve correspond to the unstable portions of the $p_c \sim q_c$ characteristics. Fig. 10(b) presents the experimental results obtained under the same operating condition as in the theoretical calculation shown in Fig. 10(a). It is seen from Fig. 10 that $p_{c1} \sim q_{c1}$ curves move in the right upper direction with an increasing q_t . From this fact, it is concluded that the effect of the total control inflow q_t does not appear explicitly only for the differential input characteristics.

Fig. 11 is a $p_{c1} \sim q_{c1}$ curve measured with the right control port blocked, i.e., $q_{c2} = 0$, and the curve indicates the calculated results from Eq. (8). The form of $p_{c1} \sim q_{c1}$ curves shown in Figs. 10 and 11 are

Fig. 11 Input characteristics on one side (right control port blocked)

different from those of other investigators, and this is due to the different definitions of the control pressure employed. In the present study, the control pressure is defined as the exit pressure of the control nozzle p_{c1} . On the other hand, in other studies, it is defined as the inlet pressure of the control nozzle p'_{c1} , so that ordinary $p'_{c1} \sim q_{c1}$ characteristics include the effect of the control port resistance. Thus, the $p'_{c1} \sim q_{c1}$ characteristics for the ordinary amplifiers with large control port resistance are naturally different from those of the tested amplifiers whose control port resistance is very small and the relation $p_{c1} = p'_{c1}$ holds. In this connection, if a large resistance restrictor is attached to the left control port of the amplifier A, the $p'_{c1} \sim q_{c1}$ characteristic curve will present the same form as ordinary $p_{c1} \sim q_{c1}$ curves as shown in Fig. 11(b).

6. Negative resistance of input characteristics

In section 4.1, the approximate form of the unstable portion of the input characteristics is estimated on the basis of the existence of a symmetrical flow of symmetrical amplifier. The validity of the approximation is investigated from a different viewpoint with the aid of Eqs. (4), (7) and (8).

The input characteristics are measured for the amplifier A with a small splitter distance $L_s/w_n = 4.5$ under the conditions of $q_t = 0$ and $\Delta Q = 0$, that is, the left and right output flows are adjusted so as to be equalized by the output valve D and E shown in Fig. 3. In this case, the characteristic curve becomes a type I curve monotonously increasing as shown in Fig. 12(a). Its functional expression is

$$\Delta \bar{q}_e = K \Delta \bar{p}_e^3 \quad (9)$$

On the other hand, when the output ports are open to the ambient through the output resistance R_o , the input characteristic curve changes its form into type II, which can be theoretically derived from Eqs. (8) and (9) under the condition $q_t = 0$ as follows:

$$\Delta \bar{q}_e = K \left(1 + \frac{K_1 d_1}{d_2 R + d_3} \right)^3 \Delta \bar{p}_e^3 - \left(\frac{K_2 d_1}{d_2 R + d_3} \right) \Delta \bar{p}_e \quad (10)$$

A solid line in Fig. 12(b) is a curve computed from Eq. (10) for $R_o = 0.03 \text{ cmAq} \cdot \text{s/cm}^3$.

Fig. 12 Negative resistance of input characteristics

As seen from Fig. 12(b), the negative slope is theoretically derived in the same form as previously estimated. From the above discussion, it is concluded that the unstable portion of the input characteristics can be approximated by means of broken lines in Figs. 4 and 8.

7. Output characteristics

The output characteristics expressed as a relation between the differential quantities $\Delta Q = Q_1 - Q_2$ and $\Delta P = P_1 - P_2$ can be theoretically derived by eliminating the variable Δp_c from Eq. (8) under the condition $q_t = 0$.

The equation is

$$\Delta \tilde{P} = \psi \left(\Delta \tilde{Q} - \frac{1}{K_2} \Delta \tilde{q}_c \right) - \frac{1}{K_2 d_2} (d_3 + K_1 d_1) \Delta \tilde{q}_c \dots (11)$$

$$\psi(\Delta \tilde{Q}) = -\frac{1}{d_2} (d_3 + K_1 d_1) \Delta \tilde{Q} + \frac{d_1}{d_2} F^{-1}(K_2 \Delta \tilde{Q}) \dots (12)$$

where F^{-1} is the inverse function of F , which is an odd function because of a symmetrical configuration of the amplifier.

Fig. 13(b) shows a systematic change of the theoretical and experimental output characteristics corresponding to a change of the input characteristics from type I to type II shown in Fig. 13(a), where both control ports are blocked in the measurement of the output characteristics. The output characteristic curve corresponding

(a) Input characteristics

(b) Output characteristics

Fig. 13 Relation of input and output characteristics

Fig. 14 Effect of control flow on output characteristics

to the input curve of type I becomes continuous and assumes the shape Λ , which presents a negative resistance* in a certain region involving the origin.

On the other hand, when the input characteristics change from type I to type II, the output characteristics also change their form into a discontinuous curve with hysteresis at the same time, the negative resistance turns to a positive one, as shown in Fig. 13(b), in which theoretical curves calculated from Eq. (11) using the input characteristics in Fig. 13(a) are represented by solid and broken lines. Theoretical results are in good agreement with experimental results involving the systematic change of the characteristics.

It is seen from Eq. (11) that the output characteristic curve influenced by the input signal ($\Delta q_c \neq 0$) is represented by a curve which is given by moving the curve $\Delta P = \psi(\Delta Q)$ for $\Delta q_c = 0$ parallel to ΔQ -axis by $\Delta q_c/K_2$ and to ΔP -axis by $-\Delta q_c(d_3 + K_1 d_1)/K_2 d_2$. The solid and broken lines in Fig. 14 are theoretical curves calculated from Eq. (11) and the input characteristics shown in Fig. 13(a). The curves are plotted with Δq_c as a parameter. Experimental results show the validity of Eq. (11).

8. Conclusions

This study has experimentally demonstrated that the input characteristics of wall-reattachment fluidic amplifiers can be expressed simply in terms of the differential quantities of the left and right sides of the amplifier. Individual variables at each control port and each output port can be solved from the differential input characteristic and other equations describing the flow in the amplifier. Simple form of the output characteristic represented by differential variables are derived from a series of equations cited. The validity is confirmed experimentally.

* $\partial \Delta P / \partial \Delta Q > 0$, i.e., $\Delta P = P_1 - P_2 > 0$ for $\Delta Q = Q_1 - Q_2 > 0$ implies that the fluid flows from the low pressure side to the high pressure side. This means a negative resistance.

[Appendix 1] System parameters used in calculation

Table 1 System parameters

	Fig. 10	Fig. 12	Fig. 13, Fig. 14	
	(i)	(ii)	(iii)	(iv)
Q_s cm ³ /s	50	50	50	50
P_s cm·Aq	24.5	24.5	24.5	24.5
P_n cm·Aq	-7.1	—	—	—
Offset	0	0	0	0
L_s/w_n	8.42	4.5	4.5	6.0
α °	12	12	12	12
w_n cm	0.19	0.19	0.19	0.19
S_n cm ²	0.228	0.228	0.228	0.228
A cm ²	0.511	0.325	0.325	0.396
S cm ²	0.480	0.480	0.480	0.480
F_x cm ²	0.460	0.220	0.220	0.186
F_y cm ²	0.27	—	—	—
R_0 cm·Aq·s/cm ³	0.032	0.030	—	—
K_1	0.011 4	0	0	0.114
K_2	0.011 2	0.054	0.054	0.020

Input characteristics of tested amplifiers

Δq_c [cm³/s], Δp_c [cm·Aq]

(i) $L_s/w_n=8.42$

$\Delta q_c=1.6\Delta p_c+3.64$, $\Delta p_c<-1.80$ cm·Aq

$\Delta q_c=-0.45\Delta p_c$, $|\Delta p_c|<1.80$ cm·Aq

$\Delta q_c=1.6\Delta p_c-3.64$, $\Delta p_c>1.80$ cm·Aq

(ii), (iii) $L_s/w_n=4.5$

$\Delta q_c=0.092\Delta p_c^3$

(iii), (iv) $L_s/w_n=6.0$

$\Delta q_c=-0.48\Delta p_c^2-1.8\Delta p_c-1.2$

$\Delta p_c<-1.78$ cm·Aq,

$\Delta q_c=-0.27\Delta p_c$

$|\Delta p_c|<1.78$ cm·Aq

$\Delta q_c=0.48\Delta p_c^2-1.8\Delta p_c+1.2$

$\Delta p_c>1.78$ cm·Aq

[Appendix 2] Method of determining F_x and F_y

Coefficients F_x and F_y are determined from the following equations using measured values P_{ci} , q_{ci} , P_i and Q_i ($i = 1, 2$).

$$F_x = \left[(A \sin \alpha) \Delta P + \left(\frac{\rho \sin \alpha}{A} \right) (Q_1^2 - Q_2^2) + \frac{\rho}{S} (q_{c1}^2 - q_{c2}^2) \right] / \Delta p_c$$

$$F_y = \left[(A \cos \alpha) (P_1 + P_2) + \left(\frac{\rho \cos \alpha}{A} \right) (Q_1^2 + Q_2^2) - S_n P_n - \frac{\rho}{S_n} Q_s^2 \right] / (p_{c1} + p_{c2})$$

An example of the experimental results for $q_{c2} = 0$ is shown in Fig. 15. In calculations of Eq. (8), mean values of F_x and F_y in the operating condition are used.

References

- (1) Kimura, M., J. Soc. Inst. & Contr. Eng., 10-4(1971), 255 (in Japanese).
- (2) Wright, C. P., Trans. ASME, Ser. D, 87-1(1965), 67.
- (3) Drzewiecki, T. M., Fluidics Q., 8-2 (1976), 1.
- (4) Ito, T. et al., Trans. Jpn. Soc. Mech. Eng., 36-321(1973), 1599 (in Japanese).
- (5) Hayashi, S. and Kamaya, S., Bull. JSME., 18-122(1975), 841.
- (6) Hayashi, S. and Kamaya, S., Bull. JSME., 18-123(1975), 1035.
- (7) Hayashi, S., Fluidics Q., 8-4(1976), 34.