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Development of Fluidic Amplifiers with High Gain and Excellent Frequency Characteristics*

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Two and three stage amplifiers in which the main jets of the first and the second stages act upon the main jet of the next stage directly without transmission line were developed as analogue amplifiers with high gain and excellent frequency characteristics. The measurements of their characteristics were carried out by using water as a working fluid. The gain characteristics were determined by measuring the flow gains. The frequency characteristics were measured by flow visualization of the jets employing a synchronized stroboscope. The gain of the two stage amplifier developed in this study was found approximately equal to that of the two stage beam deflection amplifier connected in cascade and the frequency characteristics of the amplifiers developed satisfactorily showed a constant amplitude up to 400Hz.

1. Introduction

Up to now, various types of fluidic analogue amplifiers for amplifying a fluid signal have been reported. For higher amplification, it is necessary to connect those elements in cascade. There is no problem with the method for static fluid signals, but, in case of dynamic signals, the method has a drawback in that it shows a change of the gain with an increase in frequency under the effects of inertance and capacitance of the transmission lines.

Dynamic signals in fluidics are often used in a.c. circuits. If amplifiers with high gain and excellent frequency characteristics are utilized in constructing a.c. circuits, it is considered that the circuits will give excellent performance. From this point of view, the development of amplifiers with high gain and excellent frequency characteristics was tried by connecting beam deflection amplifiers without transmission line. As a result, amplifiers with higher gain and better frequency characteristics than the two stage cascade-connected beam deflection amplifiers have been obtained.

2. Nomenclature

B_1	Maximum pressure gradient which acts on the main jet of the first stage
B_2	Maximum pressure gradient which acts on the second stage
b_1	Nozzle width
C_0	Core length
d_1	Displacement of the main jet at the point of x_1 (see Fig.15)
d_2	Displacement of the main jet at the point of y_2 (see Fig.15)

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Δf	Maximum increment of the momentum
$g_1(x, t)$	Pressure gradient which acts on the main jet of the first stage
$g_2(y, t)$	Pressure gradient which acts on the main jet of the second stage
h	Channel depth
k	Constant
M_1	Maximum displacement of the main jet of the first stage at the point of x_1
M_2	Maximum displacement of the main jet of the second stage at the point of y_2
u_{c1}	Center line velocity of the main jet of the first stage
u_{c2}	Center line velocity of the main jet of the second stage
$u(y)$	Velocity distribution of the main jet of the first stage at the point of x_1
u_{max}	Maximum value of $u(y)$
ρ	Density
ϕ_1	Phase lag of the main jet of the first stage at the point of x_1
ϕ_1'	Phase lag of the main jet of the first stage at the point of x_1
ϕ_2	Phase lag of the main jet of the second stage at the point of y_2
ω	Angular frequency

3. Configuration of the fluid amplifiers

Fig.1 shows three types of amplifiers utilized in this experiment. The fluid amplifiers shown in Fig.1(b), (c) are elements developed in this study, and they are called a compound two stage amplifier and a compound three stage amplifier respectively in this paper. The element shown in Fig.1(a) is a conventional beam deflection amplifier used for the comparison of the characteristics with the developed elements. In this case, to make the comparison possible, the dimensions of the main nozzle, the output duct and the center vent of the elements are made the same and the pressure is detected at corresponding points of each element.

Fig.1 Silhouettes of amplifiers

Fig.2 Operating principle

4. Operating principle

Fig.2 shows the operating principle of the compound two stage amplifier. When the flow rates of all the control nozzles are the same, the right and the left main jets of the first stage act on the second main jet with same momentum and consequently the second main jet does not deflect and the flow rates of the output ducts E,F are the same as shown in Fig.2 (a). On the other hand, when the flow rate of the control nozzle A is larger than

that of the control nozzle B, the first main jet of the left side deflects as shown in Fig.2(b). Consequently the momentum which acts on the left side of the second main jet decreases and the second main jet deflects to the left side and then the flow rate of the output duct E becomes larger than that of the output duct F. In this case, the deflection of the second main jet is larger than that of the first stage and thus high gain can be obtained. Moreover the first main jet acts directly to the second one without transmission line. By this means, amplifiers with excellent frequency characteristics can be obtained with the effects of the inductance and the capacitance of the transmission lines eliminated.

The control nozzles of the second and the third stages in the compound three stage amplifier serve for the adjustment of the direction of the second and the third main jets.

5. Experimental apparatus and experimental method

5.1. Construction of the amplifiers

Fig.3 shows the construction of the beam deflection amplifier in Fig.1(a). The main jet is a three dimensional free jet using the cover plate B,B'. H.M.Shaedel⁽¹⁾ reported that frequency characteristics became better as side vent length became shorter. The cover plate B,B' was used with the object of making the frequency characteristics better, and by this means, it was possible to obtain a constant amplitude of the main jet in high frequency range⁽²⁾. The element demonstrated in Fig.3 was connected in cascade with vinyl tubes of 3mm in inner diameter and 70mm in length.

Fig.4 shows the construction of the compound two stage amplifier. The main jets are three dimensional free jets with good frequency response using the cover plate B,B' as in the case of Fig.3. The compound three stage amplifier is similar in construction to the compound two stage amplifier.

Fig.5 shows the detail of the inter-

Fig.3 Construction of beam deflection amplifier

Fig.4 Construction of compound two stage amplifier

Fig.5 Details of cover plates of compound two stage amplifier
(D part of Fig.4)

Fig.6 Details of cover plate
of compound three stage amplifier

Fig.7 Experimental setup

reference region(the D part in Fig.4) of the cover plate B,B'. Three types of cover plates (Fig.5(a),(b),(c)) are tested. The cover plate (a) is the same shape with the compound two stage amplifier, the cover plate (b) is jutting beyond the element near the second supply nozzle, and the cover plate (c) is the one (b) installed with thin copper plates (0.1mm in thickness). In case of installing the thin copper plate, short transmission lines are constructed. It conflicts with the aim of this study. But the transmission lines are

short (about 2mm) and the first main jets do not flow all over the cross section of the transmission lines, therefore the baneful influence of inertance, etc. is considered to be a little.

Fig.6 shows the detail of the cover plate used for the compound three stage amplifier. It is also installed with thin copper plates as in Fig.5(c), because the cover plate (c) in Fig.5 exhibits the highest gain among the cover plates shown in Fig.5 as described below in the experimental results.

Fig.9 Static characteristics of beam deflection amplifier

Fig.13 Static characteristics of compound two stage amplifier (cover plate Fig.5(c))

Fig.10 Static characteristics of two stage beam deflection amplifier

Fig.14 Static characteristics of compound three stage amplifier

Fig.11 Static characteristics of compound two stage amplifier (cover plate Fig.5(a))

Fig.12 Static characteristics of compound two stage amplifier (cover plate Fig.5(b))

6.2. Frequency characteristics

6.2.1. Theoretical discussion on the frequency characteristics

The frequency characteristics of the compound two and three stage amplifiers are estimated theoretically based on J.M.Kirshner's theory^{(3) (4)}

At first, the case of the first main jet colliding with the second one as shown in Fig.15 is discussed under the assumption of small deflection of the first main jet.

The momentum change Δf of the first main jet at x_2 is

$$\Delta f = \rho h \int_0^{M_1} u^2(y) dy \quad (1)$$

where M_1 is the amplitude of the oscillating main jet at the splitter (x_2). $u(y)$ in developing region is described as follows by using a polynomial model.

$$u(y) = u_{\max} \left\{ 1 - 3 \left(\frac{y}{y_{\max}} \right)^2 + 2 \left(\frac{y}{y_{\max}} \right)^3 \right\} \quad (2)$$

where

$$y_{\max} = 1.35 \frac{b_1}{C_0} x_2 \quad (3)$$

which depends on Reynolds number is obtained by the following expression⁽⁵⁾.

$$C_0 = 5.2 b_1 \quad (4)$$

In this experiment, b_s is 0.5mm and x_2 is 2.5mm, and therefore the main jet is fully developed and then Eq.(2) is employed as $u(y)$. From Eq.(1), Eq.(2), Eq.(3) and Eq.(4),

$$\Delta f = \rho h u_{\max}^2 \int_0^{x_1} \left\{ 1 - 3 \left(\frac{y}{0.26x_2} \right)^2 + 2 \left(\frac{y}{0.26x_2} \right)^4 \right\} dy \quad (5)$$

The frequency characteristics of the first main jet at the splitter (x_2) are determined by developing J.M.Kirshner's theory⁽³⁾⁽⁴⁾. In this case, the pressure which acts on the second main jet does only on the region from 0 to x_1 , and does not from x_1 to x_2 , because the cover plate is bored in the region from x_1 to x_2 . Accordingly, the pressure gradient is assumed as follows.

$$g_1(x, t) = B_1 \cos \omega t \quad (0 < x < x_1) \quad (6)$$

$$g_1(x, t) = 0 \quad (x_1 < x < x_2) \quad (7)$$

In this condition, the displacement d_1 of the main jet is

$$d_1 = M_1 \cos(\omega t - \phi_1) \quad (8)$$

where

$$M_1 = \frac{B_1}{\rho \omega^2} [2[1 + \beta_1^2(1 - K_1)](1 - \cos K_1 \beta_1) + K_1^2 \beta_1^2 - 2K_1 \beta_1 \sin K_1 \beta_1]^{1/2} \quad (9)$$

$$\phi_1 = \tan^{-1} \frac{\beta_1(1 - K_1) \cos \beta_1(1 - K_1) - \sin \beta_1(1 - K_1) + \sin \beta_1 - \beta_1 \cos \beta_1}{\cos \beta_1 + \beta_1 \sin \beta_1 - \beta_1(1 - K_1) \sin \beta_1(1 - K_1) - \cos \beta_1(1 - K_1)} \quad (10)$$

where

$$\alpha_1 = \omega \int_0^{x_1} \frac{dx}{u_{c1}}, \quad \beta_1 = \omega \int_0^{x_2} \frac{dx}{u_{c1}}, \quad K_1 = \frac{\alpha_1}{\beta_1} \quad (11)$$

Next, the pressure gradient $g_2(y, t)$ is assumed as follows under the same condition as Eq.(6) and Eq.(7).

$$g_2(y, t) = B_2 \cos(\omega t - \phi_2') \quad (0 < y < y_1) \quad (12)$$

$$g_2(y, t) = 0 \quad (y_1 < y < y_2) \quad (13)$$

The pressure gradient expressed in Eq.(12) comes from the momentum of the first main jet collision which exerts influence on the second main jet. B_2 is obtained as follows.

$$B_2 = k \frac{\Delta f}{b_s h y_1} \quad (14)$$

Constant k is for the compensation of the decrease of the momentum expressed in Eq.(5) which occurs from x_2 to x_3 . ϕ_2' in Eq.(12) is derived by taking β_1' instead of β_1 in Eq.(11), where

$$\beta_1' = \omega \int_0^{x_3} \frac{dx}{u_{c1}} \quad (15)$$

Eqs.(12), (13) and Eqs.(6), (7) are of same condition. Accordingly, in the same manner as Eq.(8) we have

$$d_2 = M_2 \cos(\omega t - \phi_2) \quad (16)$$

where

$$M_2 = \frac{B_2}{\rho \omega^2} [2[1 + \beta_2^2(1 - K_2)](1 - \cos K_2 \beta_2) + K_2^2 \beta_2^2 - 2K_2 \beta_2 \sin K_2 \beta_2]^{1/2} \quad (17)$$

Fig.15 Definition of flow and configuration

$$\phi_2 = \phi_2' +$$

$$\tan^{-1} \frac{\beta_2(1 - K_2) \cos \beta_2(1 - K_2) - \sin \beta_2(1 - K_2) + \sin \beta_2 - \beta_2 \cos \beta_2}{\cos \beta_2 + \beta_2 \sin \beta_2 - \beta_2(1 - K_2) \sin \beta_2(1 - K_2) - \cos \beta_2(1 - K_2)} \quad (18)$$

where

$$\alpha_2 = \omega \int_0^{y_1} \frac{dy}{u_{c2}}, \quad \beta_2 = \omega \int_0^{y_2} \frac{dy}{u_{c2}}, \quad K_2 = \frac{\alpha_2}{\beta_2} \quad (19)$$

The frequency characteristics of amplitude and phase lag of the second main jet at y_2 are assessed by Eq.(17) and Eq.(18) and also the frequency characteristics of the third main jet can be obtained by considering the case of the second main jet colliding on the third one the same as the case of the first main jet colliding on the second one.

By these equations, the compound two and three stage amplifiers are confirmed to have excellent frequency characteristics. The calculated values will be presented in Fig.18 and Fig.19.

6.2.2 Photographs of the main jet behavior

Fig.16 demonstrates an example of the sequential photographs of the main jet behavior of the compound three stage amplifier at 400Hz. The photographs shown in Fig.16 have a defect in clearness because they are recopied from the color photographs with minicopy film. The color photographs are more distinguishable. The phase lag between the second and the third main jets and the curvature of the third main jet are recognized at 400Hz as shown in Fig.16. Fig.17 is an illustration of Fig.16.

6.2.3 Comparison of the frequency characteristics

Fig.18, Fig.19 and Fig.20 express the frequency characteristics of the compound two stage amplifier, the compound three stage amplifier and the two stage cascade connected beam deflection amplifier respectively, as measured by the flow visualization method. In this experiment, the compound two and three stage amplifiers

The amplifiers are installed with vinyl tubes of 3mm in inner diameter and 150mm in length as loads of the output ducts.

5.2. Measurement of the characteristics

In measuring the characteristics, water was used as a working fluid and the amplifiers were submerged.

5.2.1. Measurement of the gain

The comparison of the gain of the amplifiers was conducted by measuring the static flow gain.

5.2.2. Measurement of the frequency characteristics

The measurement of the frequency characteristics was performed by taking photographs of the jet behavior which was flow-visualized and synchronized with stroboscope.

Fig.7 shows the experimental setup, where the compound three stage amplifier is symbolized. The measuring principle is as follows. The flow visualization of the main jets was performed by using a red solution of NaOH(0.02N) added with a small amount of phenol-phtalein as the main jets and by using a solution of HCl(0.15N) as the control flows. By this chemical method, it is possible to observe the main jets clearly. The photographing was done as follows. At first, a fluid signal is generated by vibrating a diaphragm. The fluid signal is tuned by using as a resonator the rubber tube which is set in the transmission line. Fig.8 demonstrates an example of the tuned waveform.

The fluid signal is detected by a pressure transducer on the control nozzle of 1mm upstream from the center of the main jet. In this case, the detected fluid signal is conveyed to the receiving cavity through a sensing hole of 0.5mm in diameter and a stainless pipe. In this measurement, precaution is taken to avoid an air infiltration.

The detected signal is used as a signal to trigger the stroboscope through the amplifier and the phase shifter. In this case, the amplitudes of the detected signal and the triggering are kept constant on the oscilloscope. By this method, the flashing of the stroboscope and the movement of the main jets can be synchronized. The cover plates shown in Fig.5 and Fig.6 consist of acrylic plates and the movement of the main jets is photographed in color by the synchronized flash through the element. It is impossible to obtain good contrast by monochrome. The main jets are photographed at each phase of every 20 degree phase shift which was done with the phase shifter.

The frequency characteristics of the maximum deflection and the phase lag of the main jet at the receiver mouth are measured from the obtained photographs. The measurement of the phase lag is made by measuring the phase difference between

the input and the output signals of the phase shifter at each frequency and by making the phase lag at 10 Hz zero.

The flow rate of each main jet is $8.3 \times 10^{-6} \text{ m}^3/\text{s}$. The flow rate of the second and the third control flows are $10 \times 10^{-6} \text{ m}^3/\text{s}$ and $2.7 \times 10^{-6} \text{ m}^3/\text{s}$ respectively.

(a)

Waveform tuned with a rubber tube

(b)

Untuned waveform

Fig.8 An example of tuning of a fluid signal by use of a rubber tube (110Hz)

6. Experimental results and discussion

6.1. Static characteristics

For the comparison of the amplifiers indicated in Fig.1, the static characteristics of the element were measured.

Fig.9 shows the static characteristics of the beam deflection amplifier (Fig.1(a)). The flow gain was about 10. Fig.10 shows the static characteristics of the two stage beam deflection amplifiers in cascade. The flow gain was about 25.

Fig.11, Fig.12, and Fig.13 illustrate the static characteristics of the compound two stage amplifier with the cover plates of Fig.5(a),(b) and (c) respectively. The static characteristics shown in Fig.11 did not indicate good result, the gain being almost the same as that of Fig.9. The static characteristics shown in Fig.12 were improved considerably in comparison with those of Fig.11. The flow gain shown in Fig.13 was the highest and it was almost the same as that of the cascade connected beam deflection amplifiers.

Fig.14 shows the static characteristics of the compound three stage amplifier. The flow gain was about 35 which was higher than that of the cascade connected beam deflection amplifiers.

Fig.17 Illustrations of the photographs shown in Fig.16

used the cover plates shown in Fig.5(c) and Fig.6 respectively.

As a result, the compound two and three stage amplifiers showed a constant amplitude over 400Hz as shown in Fig.18 and Fig.19, while the two stage cascade connected beam deflection amplifiers decreased its gain as frequency increased, the decrease being about 10dB at 300Hz.

In the phase lag, the compound three stage amplifier was larger than the compound two stage amplifier, but the value was small in comparison with that of the two stage cascade connected beam deflection amplifiers.

Fig.18 and Fig.19 show the calculated value of Eqs.(17),(18) as well. The amplitude is estimated to be constant up to 800Hz and it is in accord with the axis of 0dB in the Figures. Thus, the excellent frequency characteristics of amplitude of the compound two and three stage amplifiers are also proved theoretically. But the upper limit of flat frequency response is considered to be restricted by edgetone, etc. as stated in J.M.Kirshner's theory.

As for the phase lag, the experimental and theoretical values are in good agreement, though the experimental one is

a little larger, It is considered that the reason is attributed to the effect of the short transmission lines constructed of the cover plates and the copper plates as shown in Fig.5(c) and Fig.6.

In addition to the flow visualization method, the frequency characteristics(Bode diagram) were measured with a vibration analyser and a phase meter^{(6) (7)}. By this measurement, it was also confirmed that the compound two and three stage amplifiers indicated more excellent frequency characteristics than the cascade connected beam deflection amplifiers. But the result showed that the amplitude became larger as frequency became higher and the phase lag advanced over the input signal at low frequency.

It is considered that the cause is attributed to an impedance change of the transmission line because the output signal was detected on the output duct. Furthermore, different results were obtained from different points of pressure detection. Consequently, it appears that more general results can be obtained by the flow visualization method rather than using the vibration analyser and phase meter.

Fig.18 Frequency characteristics of compound two stage amplifier (cover plate Fig.5(c))

Fig.19 Frequency characteristics of compound three stage amplifier

7. Conclusions

For the development of analogue amplifiers with high gain and flat frequency response over a wide frequency range, two and three stage amplifiers were constructed by connecting beam deflection amplifiers without transmission line, and these elements were called a compound two stage amplifier and a compound three stage amplifier respectively in this study.

The characteristics of these elements were compared with those of two stage beam deflection amplifiers which were connected in cascade with transmission lines as usually done. In comparing the characteristics, the static flow gain characteristics were measured as their gain and the frequency characteristics were measured by taking photographs of the visualized main jet behavior which was synchronized with stroboscope.

Following results were obtained. Though the gains of the compound two and three stage amplifiers were dependent on the configuration of the cover plate, the gain of compound two stage amplifier using a cover plate which showed the highest gain was almost the same as that of the two stage cascade connected beam deflection amplifiers. The gain of the compound three stage amplifier was the highest.

The movement of the main jets could be taken in distinct photographs by the flow visualization method in the region between 10Hz and 400Hz.

The frequency characteristics measured by the photographs revealed that the amplitude of the compound two and three stage amplifiers was constant up to 400Hz. On the other hand, the cascade-connected beam deflection amplifiers decreased its gain as frequency increased and the phase lag of the cascade-connected one was larger than that of the compound two and three stage amplifiers. Thus the developed amplifiers seem better in frequency characteristics than the cascade-connected one.

The excellent frequency characteristics were also confirmed theoretically based on J.M.Kirshner's jet dynamics theory.

Fig.20 Frequency characteristics of two stage cascade connected beam deflection amplifier

A defect of the developed amplifiers lies in that the consumption of the supply flow is large. But it is considered that the developed amplifiers are very useful for largely amplifying the dynamic fluid signals and for the application to fluidic a.c. circuit.

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