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On the Sensitive and Wide Frequency Range Measurement of Pressure*

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This paper presents analysing methods of the response characteristics necessary for designing a miniature pressure detector of capacitance type and electronic methods for realizing a sensitive and wide-band measurement of pressure. Several detectors, a transducer and an amplifier are prepared with the object of examining the adaptability and practicality of these methods.

Dynamic measurement and static comparative test between the present device and the other high-sensitive pressure measuring methods show that the analysis can well express the detector response to pressure and that the present method enables measurements more sensitive than the resolution of 0.002 mmAq (0.02 Pa).

Key words : Pressure Detecting Element, High Resolution,
Frequency Response

1. Introduction

Measurements of non-steady phenomena are increasingly important for studying fluid dynamics and combustion aerodynamics. Among the physical quantities such as temperature, pressure, flow velocity and concentration, pressure will be the most important one. This paper aims to obtain a pressure measuring method of high sensitivity and wide frequency range with the intention of improving the author's velocity measuring technique which is applicable to combustion field as well as ordinary temperature field.

If the probe constitution presented in Refs.(1) and (2) is used in detecting the flow velocity at a similar precision level as hot-wire velocimetry, the following specifications will be required for pressure transducers; (1) Geometrical dimension of the pressure transducer should be at most less than 10 mm. (2) The flat pressure response characteristics both of the transducer alone and of the pressure tube from the pressure head to the transducer should range from DC to the frequency of 2 kHz or higher. (3) Pressure resolution of 0.01 mmAq (about 0.1 Pa) is required. Among the various kinds of pressure transducers, one which satisfies those characteristics must be a capacitance type transducer. In particular, a condenser microphone exceeds the other types in terms of size (one as large as 2 mm in diameter can be produced)

and of sensitivity (the resolution of -60 dB = 2×10^{-7} bar = 2×10^{-8} Pa = 2×10^{-9} mmAq in absolute sound pressure level is usually attained.) The problems in using conventional pressure transducers of condenser type lie in that the low frequency pressure components are undetectable and the outputs are liable to be unstable, because the electric capacity change caused by membrane displacement is usually small in comparison to the capacity of signal cable. Consequently, if these disadvantages are removed, the pressure detecting element and amplifier of this type will have various applications.

This paper presents, first, an analysing method of the dynamic pressure response characteristics required for designing the detector and a method of construction of the amplifier; and secondly, the experimental results obtained through the development of a amplifier and a detector small enough not to disturb the measuring field.

2. Principal Symbols

- a_1, a_2 : radii of membrane and ventilation hole, respectively,
- a : distance between membrane and back pole plate,
- c : sound velocity = $\sqrt{\kappa p_0 / \rho}$,
- e_1, e_2 : thicknesses of membrane and back pole plate,
- j : complex unit = $\sqrt{-1}$,
- J_ν : ν -th Bessel function of first kind,
- k_C : electric capacitance increase factor due to dielectric substance,
- K : equivalent spring constant of membrane, = $B_0 T / a_1^2$
- l : sound equivalent length of the ventilation hole of back pole plate, = $e_2 + \pi a_2 / 2$

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- m : mass per unit membrane area, $= \rho_e l$
 p, P : pressure and pressure difference, respectively,
 r : radial distance,
 R_j : resistance coefficient of ventilation hole, $= 8\nu/a_2^2$,
 R_r : gap resistance coefficient $= 12\nu/b^2$
 s : Laplace operator, $= j\omega$
 t : time,
 T : tension per length acting on membrane,
 u, v : flow velocity directed perpendicularly from membrane and radial velocity directed inward, respectively, $u = d\xi/dt$,
 ϵ : dielectric constant of the air,
 ν : kinematic viscosity of the air,
 ξ : distance from membrane along normal,
 ξ_1 : displacement of membrane shifted perpendicularly to its surface,
 ξ_2 : length of ventilation hole,
 ρ : density of the air,
 ρ_m : membrane density,
 ω : angular frequency,
 [Superscripts]
 $\wedge$: Laplace transformed type,
 $\hat{p} = \int_0^\infty p \exp(-st) dt$,
 $-$: sectional mean value,

Relations between the engineering unit and the SI unit used in the present paper;

$1 \text{ mmAq} = 9.80665 \text{ Pa}$, $1 \text{ } \mu\text{bar} = 0.1 \text{ Pa}$,
 $1 \text{ kgf} = 9.80665 \text{ N}$.

3. Principle of Measurements

As is shown in Fig.1, the detecting element (condenser microphone) is composed of a membrane, a back pole plate and an insulation ring for electrically insulating them. They form an electric capacitance and the capacitance changes when the membrane is displaced by pressure wave (sound wave).

When pressure wave excites the membrane, the air in the gap between the membrane and the back pole plate effuses through the ventilation hole in this plate to the back space where there is no pressure change. At that time the air undergoes the mass acceleration effect of itself and the effects of the frictional resistance from the membrane, back pole plate and ventilation hole. Although the response of the membrane is subjected to friction effects such as these in addition to the mass-spring oscillation of the membrane itself, these effects have been evaluated only in a simple form [3].

Fig.1 Configuration and symbols of the condenser type pressure detecting element

This chapter tries; first, to summarize the relations among the dimensions of the assemblies, tension and mass of the membrane, and resistance component as a function of the surface-mean displacement of the membrane and; secondly, to present an evaluating method of the frequency response characteristics of the detecting element which works as a capacitance transducer. Particularly, simplifying the oscillating system in terms of the surface-mean displacement is a conventional practice, but in that case, ambiguous treatment is made such that the spring constant of the membrane is regarded as constant by the analogy of the static displacement of the membrane. This chapter describes the spring constant in a concrete form depending on the frequency.

Next we constitute an amplifier for converting the capacitance change into the voltage change which corresponds linearly to the pressure change. The response of the element itself is the subject in the present chapter, because the pressure transfer in the pressure conducting tube from the pressure head to the membrane when the detecting element is installed in a probe and the analysing method applicable to the case in which the pressure tube has temperature distribution have already been presented [4]-[7].

3.1 Response to Pressure

For the time being, we shall discuss such a case that the back pole plate has only one ventilation hole as is shown in Fig.1. If we denote the difference between the pressure at the pressure receiving side and the one at the back pole side of the membrane as p and if we neglect the electrostatic attractive force generated by the voltage imposed between the membrane and the back pole, the equation representing the membrane displacement ξ_1 will be expressed as ;

$$m \frac{\partial^2 \xi_1}{\partial t^2} - \frac{T}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \xi_1}{\partial r} \right) = P \quad \dots\dots\dots (1)$$

A particular solution [8] of the above equation excluding free oscillation solutions is expressed in the following forms;

For $i=1, 2, 3, \dots, \infty$,

$$\left. \begin{aligned} \xi_i &= \frac{J_0(\alpha_i r/a_1)}{J_1(\alpha_i)} \\ A_i &= \frac{2}{m a_1^2} \int_0^{a_1} P E_i r dr \\ \omega_i &= \frac{\alpha_i}{a_1} \sqrt{\frac{T}{m}} \end{aligned} \right\} \quad \dots\dots\dots (2)$$

$$\xi_1 = \sum_{i=1}^{\infty} \frac{A_i}{\omega_i^2 - \omega^2} E_i \quad \dots\dots\dots (3)$$

Here, symbol ω_i denotes the i -th positive root of the Bessel function of the first kind of order zero $J_0(x)$ and ω_i denotes the i -th natural angular frequency. The symbol ω is the angular frequency of the fluctuating pressure P , and in a special case of $\omega = 0$ the equation (3) coincides with the following equation of the membrane displacement against the static

pressure.

$$\xi_1 = \frac{P}{4T}(a_1^2 - r^2) \dots \dots \dots (4)$$

In order to simplify the treatment of the oscillation system, we try to express Eq.(1) in terms of the surface-mean change by integrating each term of the both sides of Eq.(1) from $r=0$ to $r=a_1$. When $\bar{\xi}_1$ is the surface-mean membrane displacement derived by dividing the volume of the rejected air by the membrane area, the average value of the second term of the left side of Eq.(1) becomes,

$$\frac{T}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \bar{\xi}_1}{\partial r} \right) = -\frac{B_\omega T}{a_1^2} \bar{\xi}_1 \dots \dots \dots (5)$$

Here, the symbol B_ω is expressed in the following infinite series,

$$B_\omega = \sum_{i=1}^{\infty} \frac{1}{\omega_i^2 - \omega^2} \bigg/ \left(\sum_{i=1}^{\infty} \frac{1}{\alpha_i^2} \frac{1}{\omega_i^2 - \omega^2} \right) \dots \dots \dots (6)$$

In the special case of $\omega_f = \omega$ in the above equation, B_ω is represented by

$$\left. \begin{aligned} B_\omega &= 8 & \text{for } \omega &= 0 \\ B_\omega &= \alpha_1^2 & \text{for } \omega &= \omega_1 \\ B_\omega &= \alpha_2^2 & \text{for } \omega &= \omega_2 \\ &\dots \dots \dots \\ B_\omega &= \alpha_i^2 & \text{for } \omega &= \omega_i \end{aligned} \right\} \dots \dots \dots (7)$$

When the coefficient $B_\omega T/a_1^2$ of Eq.(5) is denoted by K^ω and this coefficient is called an equivalent spring constant, the mean change of Eq.(1) is summarized as follows.

$$m \frac{d^2 \bar{\xi}_1}{dt^2} + K^\omega \bar{\xi}_1 = \bar{p}_1 - \left[1 - \left(\frac{a_2}{a_1} \right)^2 \right] \bar{p}_2 - \left(\frac{a_2}{a_1} \right)^2 \bar{p}_3 \dots \dots \dots (8)$$

The term P is the mean pressure from $r=a_2$ to $r=a_1$ in the gap space between the membrane and the back pole plate and it is derived by integrating the following equation of motion of the gap air.

$$\frac{\partial p_2}{\partial r} = \rho \frac{\partial v}{\partial t} + \rho R_r v \dots \dots \dots (9)$$

If positive direction of v is taken as a direction which makes r smaller, then we have

$$v = \frac{a_1^2 - r^2}{2rb} \left(\frac{a_2}{a_1} \right)^2 u_2 \dots \dots \dots (10)$$

If the velocity v at $r=a_2$ is termed v_1 , then, $\bar{p}_3$ is derived from the following equation of the pressure change at the parts from $r=0$ to $r=a_2$ of the gap,

$$\frac{d\bar{p}_3}{dt} = -\frac{\rho c^2}{a_2 b} (a_2 u_2 - a_2 u_1 - 2b v_1) \dots \dots \dots (11)$$

and from the following equation of the air motion in the ventilation hole for which ξ_2 is taken as the axial distance of the hole.

$$\frac{\partial p}{\partial \xi_2} = -\rho \frac{\partial u_2}{\partial t} - \rho R_f u_2 \dots \dots \dots (12)$$

After deriving the function $p_2(r)$ by integrating Eq.(9), the mean pressure p for the ringed part from $r=a_2$ to $r=a_1$ is

derived. Through the integration of the pressure p of Eq.(12) for the range from $p=\bar{p}_3$ at $\xi_2=0$ to $p=0$ at $\xi_2=l$, and by the use of both the approximation, $\bar{u}_1 \approx u_1$, and the equation (11), the equation for $\bar{p}_3$ is derived. Respective equations are then summarized by the use of $\bar{u}_1 = d\bar{\xi}_1/dt$. The Laplace transform types of $\bar{\xi}_1$ and $\bar{p}_1$ are termed $\hat{\xi}_1$ and $\hat{p}_1$, respectively. By summarizing them in the form of the response of the membrane $\hat{\xi}_1$ to the pressure $\hat{p}_1$, the following equation is finally derived.

$$\frac{K \hat{\xi}_1}{\hat{p}_1} = \frac{1}{1 + (m/K)s^2 + (s/K)(X_b/X_a)} \dots \dots (13)$$

Where the symbol s denotes Laplace operator and, by the use of this operator the terms K , X_a and X_b are represented as;

$$K = \frac{T}{a_1^2} \sum_{i=1}^{\infty} \frac{1}{\omega_i^2 + s^2} \bigg/ \left(\sum_{i=1}^{\infty} \frac{1}{\alpha_i^2} \frac{1}{\omega_i^2 + s^2} \right),$$

$$X_a = \frac{bl}{c^2} s(s + R_f) + \left(\frac{a_2}{a_1} \right)^2$$

$$X_b = \rho \left\{ l(s + R_f) + \frac{a_2^2}{8ba_1^4} \left[4a_1^4 \ln \frac{a_1}{a_2} - (3a_1^2 - a_2^2)(a_1^2 - a_2^2) \right] (s + R_r) \right\} \dots \dots \dots (14)$$

In a special case, when the air resistance between the membrane and back pole is disregarded, then X_b is simplified to the first term $\rho l(s + R_f)$ only.

In the case when the back pole plate has n -ventilation holes of radius a_2 , the membrane displacement is accompanied with a circumferential change. Because it is difficult to solve analytically this change, the membrane response is estimated by the following approximate methods; (1) Ventilation holes are regarded as being concentrated in the center of the plate and the air excluded by a displacement of the membrane of radius a_1 is assumed to be discharged through one hole of radius $\sqrt{n}a_2$ into the back space. (2) The holes are regarded as being drilled uniformly over the back pole surface, hence, the air excluded by a displacement of the membrane of radius $a_1/\sqrt{n}$ is assumed to be

Fig.2 Electric capacitance change for membrane displacement

discharged through the holes of radius a_2 into the back space.

The functions X_a and X_b derived from both the standpoints coincide respectively with the equation of which the term a_1 in Eq.(14) is replaced with the term $a_1/\sqrt{n}$ and the one of which the term a_2 is replaced with the term $\sqrt{n}a_2$. The equations which use these approximations are incapable of giving an exact estimation of the higher order radial oscillation; however, from the practical sense we shall make sure in the experiments in the subsequent chapter which approximation method would give a more accurate solution with respect to the response of the membrane displacement for plural ventilation holes. At the same time, we shall examine the effect of neglecting higher order harmonic oscillations on the membrane response in the frequency range lower than the first order harmonic oscillation.

3.2 Electric characteristics and detecting methods

The electric capacitance C_0 induced between the membrane and the back pole plate in case of no pressure acting on the membrane is expressed as ;

$$C_0 = \frac{k\epsilon S_1}{b} \dots\dots\dots(15)$$

Where, S_1 denotes the membrane surface area πa_1^2 . When the membrane is displaced by a loading pressure, the capacitance C is regarded as the aggregate of the electrostatic condenser of the ringed membrane of radius r and width dr as is shown in Fig.2; hence,

$$dC = \frac{k\epsilon dS_1}{b - \xi_1} \dots\dots\dots(16)$$

The capacitance change obtained by substituting Eq.(3) into the displacement ξ_1 coincides with the one in the case that the plate is moved parallel as much as ξ_1 .

Put $C = C_0 + \Delta C_0$ then

$$\frac{\Delta C_0}{C_0} = \frac{\xi_1}{b} \dots\dots\dots(17)$$

The term ξ_1 corresponds to the pressure change in the transfer function form of Eq.(13). In the special case for static pressure, the above value is equal to $a_1^2 \bar{p}_1 / (8Tb)$, and from the later mentioned calculation the actual value almost coincides with this value if the

frequency is lower than the first resonance one ω_1 . Therefore, it becomes possible to evaluate the pressure p by converting the relative change $\Delta C_0 / C_0$ to an electric signal.

Figure 3 shows a simplified instance of the sound pressure detecting circuit of an electret condenser microphone combined with field effect transistors (FETs). The principle of this microphone differs from that of the usual condenser type transducers in that the element dispenses with the DC voltage for polarization but is similar to the usual ones in detecting the relative change $\Delta C_0 / C_0$ which varies according as the pressure changes. The circuits such as these, however, are inapplicable to detecting the low frequency components (less than several Hz) of pressure. And this defect is the weakest point which has rejected the use of microphone as a pressure measuring tool.

The second object of the present paper lies in removing this defect and in fabricating a practical amplifier capable of measuring the pressure ranging from DC to high frequency components. To attain this object there are several methods available such as the one which uses an alternating current Wheatstone bridge [9] and the one using a resonance circuit, and a method of amplitude modulation and one of frequency modulation [10].

Trial fabrication and test showed that the amplitude modulation method with resonance circuit, which will be described later, has high sensitivity and wide frequency range characteristics and satisfies the specification for applicability to the velocity measurements.

Now, we discuss the case that a high-frequency current power source I of constant current amplitude and of carrier angular frequency of ω_h is connected to the LC series-parallel circuit which consists of inductance L and capacitance C as is shown in Fig.4.

$$I = I_m \exp(j\omega_h t) \dots\dots\dots(18)$$

The symbol C in the figure represents the electric capacitance of the element, L indicates the inductance of the coil connected in series to C , C_1 denotes the distributed capacitance of the signal lines and L_1 means the inductance of the coil connected in parallel to C_1 . The

Fig.3 Construction and circuit of an electret type condenser microphone

Fig.4 Model of a detecting element

99.99 purity aluminum of 0.5 μm thick with the back pole plate in the form shown in Fig.1. The element which has high fundamental resonance frequency over 30 kHz was prepared as a standard element, and in comparison with this element, those several testing elements of low natural resonance frequency were prepared, which differed in membrane thickness, tension, gap distance, and ventilation hole numbers and dimensions. From the comparison of the output signals between the standard element and the testing one placed side by side in a speaker sound field, we measured the experimental values which correspond to the transfer function obtained by substituting $j\omega$ in Eq.(13) instead of s . This measurement was carried out under the pure sound analysing condition with use of a signal analyser, SM2100, IWASAKI Co.

4.2 Amplifier and measuring method

Figure 5 shows an amplifier circuit constituted on the basis of the principle of Sec.3.2 and Fig.6 indicates its operation. As an oscillation circuit, a crystal sinusoidal oscillator with a driving circuit (oscillation frequency 456 kHz, frequency stability of 10^{-7} or less) was used. RF-amplifier and rectifier as well as driving circuit

Fig.8 Response characteristics of the pressure detecting element

Fig.9 Response characteristics of the pressure detecting element

require the characteristics of wide frequency, high speed, high input impedance and low temperature coefficient of offset voltage and current; hence discrete integrated circuits (Transistors, FET-Tr.) and operational amplifiers (CA3001, OP-17) were used for fabricating them.

The static characteristic test has been carried out with the use of a Pitot-type pressure detector shown in Fig.7. In this detector is incorporated the detecting element which will be submitted to a dynamic characteristic test shown in figure 8 mentioned later. The front end of the stainless pipe 1 is connected to the straight and the branch pipes. The former pipe was placed in the low turbulence wind-tunnel for loading a dynamic pressure and the latter pipe was branched from the former one and was connected to the other pressure detectors for comparison.

For a comparison test are used a submerged bell type detector and a reluctance type manometer. The former detector is the one which has been used as the pressure standard apparatus but has a larger size (S-Co., size $\phi 125 \times 160$, resonance time 20 sec, resolution 0.002 mmAq). The latter one has comparatively high response frequency and small size (manufactured by T-Co., size $70 \times 40 \times 40$, response DC to 1 kHz., resolution 0.005 mmAq) in comparison with the former one. These detectors as well as the present detector are differential type and the static test was executed by placing the other pressure input ends in an atmospheric pressure state.

5. Results and Discussions

5.1 Dynamic tests

Figures 8 to 10 compare the experimental results with the calculated ones in the amplitude and phase of the transfer function $K\dot{\xi}/p$ of the pressure detecting element. Figure 8 shows the results under the conditions of membrane

Fig.10 Response characteristics of the pressure detecting element

thickness of 40 μm , six ventilation holes of diameter $\phi 0.78$ drilled circumferentially on a concentric circle of radius 2 mm and natural frequency 6.8 kHz.

In this calculation it is considered that six holes are concentrated in the center. The dot-dash lines show the results (Results I) taking into account the oscillation orders up to 20th, the solid lines the results (Results II) considering only the fundamental one and the dash lines the approximated results neglecting the air resistance and the inertia forces which act on the air between the back pole plate and the membrane. The calculated results in Figs. 9 to 10 are based on only the first order oscillation. In Fig.9 a 12.5 μm thick membrane is used and the gap distance from membrane to back pole plate is taken as a parameter. Fig.10 concerns the case when that is one ventilation hole and its diameter is changed. Because experimental results in these three figures are accompanied with complex variations in the higher frequency ranges, only the experimental points below the second resonance frequency are shown.

From the comparison between the calculated and experimental results in Fig.8, it is evident that the simple analysis which neglects inertia and friction force of the gap air yields large differences from the actual values.

It is also understandable that the simplified estimation taking into account only the first order oscillation (result II) gives a curve which is almost the same as the result II in the frequency range lower than the first resonance frequency (natural freq.) and yields a satisfactory approximation to the actual response characteristics.

The calculated curves when six ventilation holes are regarded as uniformly drilled are not indicated but these curves agree almost with the dash-lines. Therefore, the assumption that six holes are concentrated on the center

Fig.11 Comparison with the submerged type manometer

of the back pole plate gives superior results to this case.

In the cases of Figs.9 and 10, the frequency response becomes flatter and the first peak becomes smaller with a decrease in gap distance and ventilation hole diameter, that is, with an increase in friction force. Because every calculated result showed good agreement with the experimental one, it can be concluded that the present methods of analysis may be applicable to the designing of the pressure detecting element.

5.2 Static characteristics

Figure 11 shows the experimental curves when the output of the bell-type pressure transducer is recorded as abscissa and that of the present device as ordinate. The recorded curve is non-linear in the region below $p = 0.2 \text{ mmAq}$ ($\approx 2 \text{ Pa}$) and above this pressure it is accompanied with a slight stage-like change according as the dynamic pressure increases. This nonlinearity comes from the fact that the flow velocity (dynamic pressure) applied to the detectors could not be increased so gradually without causing flow turbulences that the bell-type transducer of long response lag characteristics follows a pressure change. Excluding the non-linear parts, it can be said that the present outputs have linear relationships with those of the bell-type pressure transducer.

Fig.12 Measurement of the working range of the transducer

Fig.13 Comparison of the drift characteristics

Figure 12 compares the test results in the pressure increase and decrease state between the present device and the reluctance type pressure transducer. Due to the effects of the hysteresis of the membrane and of the second order small terms which are neglected in the analysis, linearity deteriorates at an overload state greater than $p=3$ mmAq and the record comes to show a hysteresis loop. However, it is seen that within the pressure range below 3 mmAq they have perfect linearity and therefore the present device will be effective for the practical use. The pressure range which causes no hysteresis loop is the working range of the detector, and this range can be altered freely by changing the thickness and tension of the membrane.

Figure 13 shows as well the comparison records with respect to zero drift test. These tests were run under the same difference pressure condition where the both detector ports of high and lower pressure inputs were opened to the atmosphere; hence, the recorded curves should hold ideally zero. Comparatively short period fluctuation and long period variations are however seen in the records. The former are the result of that the atmospheric pressure change generated by the outdoor noise and wind having propagated to the both membrane sides at different amplitudes and with time lag; therefore, these fluctuations may be excluded from the drift of the apparatus. However, even though these are the fluctuations in the short period, it would be better to use a detector of small drift. In this respect, the present one is found superior and this is because of the simple construction of inside configuration and the smaller size. The curve of long surge indicates the drift and minimum resolution of the transducer. Judging from the experimental records, the resolutions of both detectors are found to be of the order 2/1000 to 5/1000 mmAq.

The following are the conclusions reached on the basis of the electric performance of the present circuit. The frequency drift of the oscillator is 0.5 Hz per hour at the oscillator frequency of 456 kHz. This value corresponds to a pressure drift of 0.002 mmAq, and this value produces negligible changes within the period of experimental record.

As can be estimated from the following equation derived from Eq.(17);

$$\frac{\Delta C_0}{C_0} \approx \frac{\alpha_1^2}{8bm\omega_1^2} p_1 \dots\dots\dots (26)$$

and from the equations from (19) to (22), the sensitivity of the present method can be increased in the following ways: (1) decreasing m and ω_1 , (2) making the denominator of the second factor of Eq.(19) closer to zero by shifting the tuning point, and (3) making ω_h , I_m larger. Therefore, it is possible to specify the optimum membrane thickness, tension and amplifier specifications depending on the magnitude and frequency range to be measured, thus the resolution can be improved to more than the above mentioned value.

6. Conclusions

In this report, the analysing methods of the dynamic characteristics of the condenser type pressure detector which is composed of membrane and back pole plate are given, the constitution method of the amplifier is indicated, several kinds of pressure detecting elements and amplifiers are developed, and the dynamic and static characteristics are examined. Through the comparisons between the experimental and the calculated results, the following conclusions have been obtained.

(1) By the use of an equivalent spring constant composed of an infinite series of B_ω in Eq.(6), it is possible to express the response of the pressure detecting element to a pressure fluctuation in the form of mean displacement equation (13).

(2) The inertia and friction force of the air at the gap between the membrane and the back pole should be considered in analysing the dynamic response of capacitance type pressure detecting element; however, with respect to the frequency response below natural frequency, the analysis using only the first order gives results which differ little from the exact ones obtained by considering higher order harmonics.

(3) The pressure detector and amplifier showed a pressure resolution of 0.002 mmAq, which is almost on the same level as the highest available performance.

Considering that the detector is a small one, it has therefore a much wider frequency band than the devices used for comparison tests and that the pressure detecting performance may be improved by altering the specifications of the amplifier and by choosing a better type of membrane, it can be said that the present method is fully practical and applicable for various uses.

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