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An Experimental Study on the Hovering Characteristics of Two-dimensional Peripheral Jet Type GEM

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Summary

The hovering characteristics of two-dimensional peripheral jet type GEM were investigated experimentally. The study was made with the purpose of finding out an appropriate method of analysis as well as understanding the hovering characteristics.

The experimental data were analyzed on the basis of dimensional analysis and as the result, some approximate expressions for hovering characteristics in terms of properly chosen parameters were obtained. Although the agreement between the experiments and the conventional theories were not very good, the approximate expressions obtained in the present study were somewhat similar to those derived from the simple momentum theory.

1 Introduction

The work described herein concerns the experimental investigation of the hovering characteristics of two-dimensional peripheral jet type GEM which hovers over the solid surface horizontally and at zero forward speed.

The investigation is made with the purpose of finding out the most appropriate method of analysis as well as grasping the hovering characteristics.

The major quantities which represent the hovering characteristics are total lift, static pressure exerted over the base of the machine which is called 'cushion pressure', volume flow rate of air which should be delivered to the peripheral nozzle and total pressure of jet at nozzle exit.

These quantities are greatly influenced by such parameters as the jet discharge angle, hover-height of the machine, nozzle thickness at the exit, etc.

Several attempts have been made theoretically to find the correlation among these characteristic quantities and parameters by Chaplin, ⁽¹⁾⁽²⁾ Jones, ⁽³⁾ Strand, ⁽⁴⁾⁽⁵⁾ Ehrich ⁽⁶⁾ and others. At an early stage of the study, the works conducted by these investigators were effective enough to give us an outline of the hovering characteristics.

Especially, both of the methods proposed by Chaplin and by Jones are still often used for rough estimation of the hovering performance for the sake of their simplicity. However, all of these theories are in common based on the assumptions that the motion of jet is an inviscid irrotational flow and that in the region enclosed by the lower surface of the machine, the ground and two peripheral jets on both sides, the fluid is at rest and consequently the cushion pressure is constant throughout the region. The fact is, however, largely different from these assumptions. The effect of viscosity on the jet motion is considerable, which is visualized in Fig. 1. Fig. 1 is one of the results of water flow tests

Fig. 1

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conducted at the Mitsubishi Research Laboratory in 1961. Water is used instead of air and the flow pattern under the base of the model is clearly shown by the crowding together of aluminum filings scattered on the water. Fig. 1 shows that the mixing of jet with the adjacent fluid is remarkable and besides, in the region enclosed by the lower surface of the model, the ground board and jets, a vortex motion is brought on due to viscosity, which will probably affect the pressure distribution over the lower surface of the model, consequently the hovering characteristics. Therefore, the application of these theories to the practical estimation of the hovering characteristics after all requires very complicated corrections based on experiments. It seems that, so far as we rely on the theory too much, which is not complete enough as yet and try to obtain 'forcibly', so to speak, such results as will be in good agreement with actual phenomena, this complexity can not be helped.

The author, by retracing his steps and on the basis of experimental investigations, attempts to find out the method of analysis of the hovering characteristics. The major problems are, therefore, how to choose or define the parameters which supposedly affect the hovering characteristics and, by making use of them, how the hovering characteristics should be represented as accurately as possible.

In the present study, the dimensional analysis is applied to the analysis of the experiment, and one parameter which has the dimension of pressure is newly defined instead of cushion pressure. For convenience, this parameter will be called "nominal cushion pressure" through the present paper.

By virtue of defining this parameter, the method of experiment and analysis seems to become simpler than ever.

2 Experiment

The schematic diagram of experimental set up is shown in Fig. 2. The model consisted of three major blocks, i.e. the outer block, the base board and the ground board. The ground board was movable vertically in order to adjust the hover-height (and was also to be inclined in case of testing the static stability), while the first two blocks were fixed to the tank.

Fig. 2

Fig. 3

Table 1

Model No	type	t mm	θ°	B mm	r mm	A mm	ϵ mm
1		10	20	600	20	51.6	40
2		10	30	600	-	64.6	-
3		15	-	580	-	-	-
4		20	-	560	-	-	-
5		10	-	600	-	56.0	10
6		10	45	-	15	39.8	40
7		10	60	-	-	36.2	-

Tests were made on seven different types of models, the leading dimensions and geometric details of which are given in Fig.3 and Table 1.

The ground board, 2m in breadth and 0.4m in depth was common to all the models. Pressure taps were installed at 63 points along the center line of the ground board. Total lift was obtained by integrating the pressure distribution over the ground board. In addition to this, the measurement of the pressure distribution over the base board was made particularly on the type 2 model.

The volume flow rate of air was measured by means of an ordinary orifice. The measurement of mean total pressure at nozzle exit is usually very troublesome and difficult because the total pressure distribution across a very narrow exit must be known.

In some of the conventional studies, the maximum total pressure (or the total pressure at some reference point) has been taken in place of mean total pressure. In the present study, mean total pressure was obtained in the following calculation.

Denoting total pressure in plenum chamber by H_T and duct loss coefficient of a model out of ground effect by ζ_0 , total pressure at nozzle exit H_j is approximately represented as follows :

$$H_j = H_T - \zeta_0 \frac{\rho}{2} \bar{V}_j^2$$

so that

$$\frac{H_j}{\frac{\rho}{2} \bar{V}_j^2} = \frac{H_T}{\frac{\rho}{2} \bar{V}_j^2} - \zeta_0$$

Where ρ is density of air and $\bar{V}_j$ is mean velocity of jet at nozzle exit. Strictly speaking, the duct loss coefficients in ground effect may possibly differ from those out of ground effect ζ_0 . However, because the values of ζ_0 were small compared with $H_T / \frac{\rho}{2} \bar{V}_j^2$ during the test, the above approximation seemed fairly true. Thus, mean total pressure of jet at nozzle exit was indirectly obtained by measuring the total pressure in plenum chamber and the duct loss coefficients of models out of ground effect. (In plenum chamber, dynamic pressure of air was negligible and total pressure was almost equal to static pressure.)

3 Method of Analysis

As already mentioned, the hovering characteristic is represented by mean cushion pressure $\bar{A}p$, volume flow rate of air which should be delivered to the peripheral nozzle Q , mean total pressure of jet at nozzle exit H_j and total lift L .

In the first place, we consider mean cushion pressure $\bar{A}p$. By virtue of the up-to-date experiences obtained either experimentally or theoretically, it is easily inferred that the parameters which possibly have considerable effect on $\bar{A}p$ are density of air ρ , mean jet velocity $\bar{V}_j$, nozzle thickness at exit t and mean radius of curvature of jet R . Besides these parameters, we take viscosity of air μ . Thus

$$f(\bar{A}p, \rho, \bar{V}_j, t, R, \mu) = 0 \quad (1)$$

According to Buckingham's theorem, eq. (1) is written, using three non-dimensional quantities which are independent one another, in the form

$$\Phi_1\left(\frac{\bar{A}p}{q_j^*}, \frac{t}{R}, R_e\right) = 0 \quad (2)$$

where $q_j^* = \rho \bar{V}_j^2 / 2$ and $R_e = \rho \bar{V}_j t / \mu = \bar{V}_j t / \nu$

The determination of the form of the function Φ_1 in eq. (2) is beyond the dimensional analysis and is to be made experimentally.

Although it is a difficult question how the mean radius of curvature of jet R should be taken, we adopt here the conventional way of expression, according to which jet exhausted from the nozzle is assumed to form a circular arc tangential to the ground.

Thus

$$R = \frac{h}{1 + \cos \theta}$$

and if, for simplicity, we put

$$x = \frac{t(1 + \cos \theta)}{h}$$

We obtain

$$\frac{\bar{\Delta p}}{q_j^*} = \phi_2(x, R_e) \quad (3)$$

In practice, however, it is a great nuisance to measure the value of $\bar{\Delta p}$ and accordingly, might give arise to extra errors in measurement, since it is usually obtained by integrating the static pressure at a large number of points over the lower surface of the model. In order to keep out these nuisances, a parameter Δp^* which has the dimension of pressure will be defined and called "nominal cushion pressure" for convenience.

$$\Delta p^* = \frac{L - J \sin \theta}{S} \quad (4)$$

where $J = \rho S_j \bar{V}_j^2$, which represents the momentum flux of jet across the nozzle exit in a particular case that the motion of jet is ideal and besides, the velocity distribution of jet across the exit is constant.

On the r.h.s. of eq. (4), θ and S are constant and then all that should be measured are L and J . The total lift L is easily measured with considerably high accuracy. Furthermore, since

$$J = \rho S_j \bar{V}_j^2 = \rho S_j \left(\frac{Q}{S_j} \right)^2,$$

we can obtain the value of J through the measurement of Q which is in usual carried out by means of the elaborately calibrated orifice. Thus it seems that the definition of Δp^* enables us to conduct the experiment more simply with higher accuracy.

We now examine the relation between $\bar{\Delta p}$ and Δp^* . If we represent the actual jet momentum flux across the nozzle exit by λJ and mean static pressure of jet by $\kappa \cdot \bar{\Delta p}$, respectively, where λ and κ are nondimensional coefficients, the total lift L is approximately expressed as follows:

$$L = \bar{\Delta p} S + \lambda J \sin \theta + \kappa \cdot \bar{\Delta p} S_j \cos \theta \quad (5)$$

therefore

$$\bar{\Delta p} = \frac{L - \lambda J \sin \theta}{S \left(1 + \frac{S_j}{S} \frac{\kappa}{\cos \theta} \right)} \quad (6)$$

In the ordinary GEM, θ ranges from 30° to 60° and S_j is very small compared with S , i.e. $S_j/S \ll 1$. And also, for the rough estimation it may be reasonable to consider that λ has a value close to unity and that κ ranges from 0 to 1. With this in mind and comparing eq. (4) with eq. (6), we may conclude that Δp^* might have a value of the same order as that of $\bar{\Delta p}$. In order to ascertain whether or not this conjecture is right, the comparison between $\bar{\Delta p}$ and Δp^* is made experimentally concerning the type 2 model. The ratio $\Delta p^*/\bar{\Delta p}$ is plotted in Fig. 4 as a function of x for the type 2 model. Fig. 4 shows that, although $\Delta p^*/\bar{\Delta p}$ is slightly affected by x , its value is approximately equal to unity in the practical range of x , i.e. $0.3 \leq x$ and that the deviation from unity is at most 0.05 through the same range of x .

Considering this fact, we now replace $\bar{\Delta p}$ in eq. (3) by Δp^* and define "pressure coefficient" C_p as follows:

$$C_p = \frac{\Delta p^*}{q_j^*} = \Phi(x, R_e) \quad (7)$$

The experimental values of C_p are plotted against x in Fig. 5 along with the calculated curve based on Jones' exponential theory which has, so far, been considered to be in the best agreement with actual phenomena. Fig. 6 represents a plot of C_p against R_e for two values of x concerning the type 2 model.

Fig. 5 and Fig. 6 suggest us that the effect of R_e on C_p is small compared with that of x and that the difference of R_e seems to influence C_p only to the same degree as those of other subsidiary factors such as the dimensions and geometric details of duct near the nozzle exit, for example, the radius of curvature of the bend, etc. (i.e. the difference of a, b, r, in table 1). Especially in the range $R_e \geq 3 \times 10^4$, we may reasonably

conclude that the effect of R_e is almost negligible compared with that of x . As almost all the present experiments have been conducted in the range $3 \times 10^4 \leq R_e \leq 8 \times 10^4$, we will take no account of the effect of R_e .

This enables us more easily to find out the form of the function Φ . In Fig. 5, it is seen that the experimental points, as a whole, lie on a straight line on log-log graph independently of the different dimensions and geometric details of duct near the nozzle exit which seven different types of models respectively have as described in 2. This fact indicates that C_p is approximately expressed in the form

Fig. 4 $\Delta p^*/\bar{\Delta p} \sim x$

Fig. 5 $C_p \sim x$

Fig. 6 $\Delta p^*/q_j^* \sim Re$

$$C_p = \frac{\Delta p^*}{q_j^*} = m x^\alpha \quad (8)$$

where m and α are non-dimensional quantities, which are determined from the analysis of Fig. 5 as follows:

$$m = 1.95 \quad \alpha = 1.26$$

By substituting these values in eq. (8), we obtain an approximate expression for C_p , the deviation of which from the corresponding true values is at the most $\pm 10\%$ or so.

It is to be noted that, if we put $\Delta p^* = \bar{\Delta p}$, $m=2$, $\alpha=1$, in eq. (8), we obtain an expression identical with that derived from Chaplin's thin jet theory.

We can also see from Fig. 5 that, even though we take into account the difference between $\bar{\Delta p}$ and Δp^* , the discrepancy

between the theory and the experimental results is considerable and that very complicated corrections will be necessary to obtain reasonable results theoretically.

We next consider total lift L . By virtue of defining Δp^* , this also is expressed in a simpler form, otherwise its expression is fairly complicated as previously shown in eq. (5).

From eq. (4)

$$L = \Delta p^* S + J \sin \theta \quad (9)$$

Substituting eq. (8) and $J = 2S_j q_j^*$ in the above equation and defining total lift coefficient $C_L = L/q_j^* S$, We obtain

$$C_L = \frac{L}{q_j^* S} = C_p + 2 \sin \theta \frac{S_j}{S} \quad (10)$$

Then the expression for volume flow rate of air Q is easily obtained.

$$Q = S_j \bar{V}_j = S_j \sqrt{\frac{2}{\rho} \frac{L}{S C_L}} \quad (11)$$

The expression for mean total pressure at nozzle exit H_j is also determined by assuming that it is a function of ρ , t , $\bar{V}_j$, R and μ , and adopting the similar method of dimension to what has been used previously in the analysis of $\bar{\Delta p}$.

Thus

$$\Psi\left(\frac{H_j}{q_j^*}, x, Re\right) = 0 \quad (12)$$

Fig. 7 $H_j/q_j^* \sim x$

The experimental values of H_j/q_j^* are plotted in Fig.7 against x , and also in Fig.8 against R_e for two values of x concerning the type 2 model.

These two plots suggest us that the effect of R_e is almost negligible compared with that of x in the range $R_e \geq 3 \times 10^4$ and that the function ϕ seems to be expressed approximately in the form

$$C_H = \frac{H_j}{q_j^*} = n x^\beta + \lambda_0 \quad (13)$$

where $C_H = H_j/q_j^*$ will be called "total pressure coefficient".

Analyzing Fig.7, the values n, β and λ_0 are determined as follows :

$$n=1.13 \quad \beta=1.71 \quad \lambda_0=0.82$$

If we substitute the above values in eq. (13), we obtain the full line in Fig.7, by which C_H is represented with the error less than 10% or so.

It is to be noted that, if we put $n=\beta=\lambda_0=1$ in eq. (13), the identical expression with that derived from Chaplin's thin jet theory is obtained.

4 Application to Design

The previous investigation has enabled us to express each of L, H_j and Q as a function of the parameters x, θ, S_j, S , etc. We consider herein how to apply these results to practical design,

Since in the ordinary GEM, the fan supplies the peripheral nozzle with air, we will find out expressions for required total pressure $H_{req.}$, volume flow rate Q and shaft horse power P_F of the fan.

Defining the duct loss coefficient

$$\zeta = \frac{\Delta H}{q_j^*}$$

where ΔH is the dissipated total pressure of air flow through the duct which connects the fan to the peripheral nozzle, we obtain

$$H_{req.} = H_j + \zeta q_j^* = q_j^* (C_H + \zeta) \quad (14)$$

and from eq. (11)

$$Q = S_j \sqrt{\frac{2}{\rho} \frac{L}{S C_L}}$$

Denoting the fan efficiency by η_F , we obtain

$$P_F = \frac{H_{req.} Q}{\eta_F} = \frac{1}{\eta_F} S_j \sqrt{\frac{2}{\rho} \left(\frac{L}{C_L S} \right)^{3/2}} (C_H + \zeta) \quad (15)$$

The above equation is written by defining "shaft horse power coefficient" C_{PF} as follows :

$$C_{PF} = \frac{P_F}{\frac{1}{\eta_F} \sqrt{\frac{2}{\rho} \frac{L}{S}}} = \frac{C_H + \zeta}{C_L^{3/2}} \left(\frac{S_j}{S} \right) \quad (16)$$

where $S_j/S = 2(t/h)(h/B)$ in the present case of two dimensional GEM. It now seems reasonable to take $t/h, h/B$ and θ as parameters instead of taking x as one of the parameters so far as C_{PF} is concerned.

Fig.9 represents a plot of eq. (16) for $\zeta=0.7, \theta=45^\circ$ which is calculated using the values of m, n, α, β and λ_0 obtained in the previous analysis.

It is interesting to note that there is an optimum value of t/h which is almost independent of the value h/B . At a value t/h of about 0.7 there is a minimum point in the curve, and from here on C_{PF} rises slowly with further increases in t/h , while below $t/h=0.7$, there is a very rapid variation with t/h . It is also remarkable that in the practical range of h/B , i.e. $h/B \leq 0.1$, the effect of t/h on power coefficient is very small provided that t/h ranges from 0.5 to 1. This fact, however, does not mean

Fig.8 $H_j/q_j^* \sim R_e$ 曲線

Fig. 9 $C_{PF} \sim t/h$

for hovering characteristics have been obtained. These expressions are somewhat similar to those derived from Chaplin's thin jet theory except that the constants (coefficients, exponents, etc.) included therein are considerably different from those in the theoretical expressions.

(3) In the range $Re = \bar{V}_j t / \nu \geq 3 \times 10^4$, the effect of Reynolds' number on C_P and C_H is negligible compared with that of $x = t(1 + \cos \theta)/h$.

(4) Defining the parameter $\Delta p^* = (L - J \sin \theta)/S$ instead of the mean cushion pressure $\bar{\Delta p}$ seems to make the method of experiment and its analysis simpler and to enable hovering characteristics to be expressed in simpler forms. The magnitude of Δp^* is almost the same as that of $\bar{\Delta p}$ in the usual range of x .

(5) Almost independently of the height-breadth ratio h/B , the power coefficient is a minimum at a value t/h of about 0.7. Furthermore, in the ordinary range of h/B (i.e. $h/B \leq 0.1$), the effect of t/h on power coefficient is very small provided that t/h ranges from 0.5 to 1.

In addition to the above conclusions, some further remarks are to be made.

(1) During the present analysis, we have not taken into account the different dimensions and geometric details of duct near the nozzle exit which seven types of models respectively have, and averagely determined the unknown m, n, α , etc. However, these subsidiary factors may to some extent affect hovering characteristics, and it thus appears that the deviation of experimental points from their mean line may be partly due to the effect of these subsidiary factors. In order to grasp these subsidiary effects, however, a large number of systematic model tests will be necessary.

(2) In consequence of the further investigation, the same method of analysis has turned out to be applicable to three-dimensional case though the constants m, n, α , etc. are different from those in two-dimensional case.

that we can arbitrarily choose a value of t/h . The ratio t/h not only affects the power coefficient but also influences the values Q and H_{req} . In other words, t/h changes the combination of the values Q and H_{req} . with the product $Q \cdot H_{req}$ kept constant. Therefore, we should choose a value t/h which gives such a combination of Q and H_{req} as will make the fan efficiency as high as possible.

5 Conclusion and Remarks

The conclusions obtained from the previous investigations are as follows ;

- (1) Very complicated corrections seem to be necessary if we, on the basis of theory, try to represent hovering characteristics in a wide range of $t(1 + \cos \theta)/h$.
- (2) By applying the method of dimensional analysis to the analysis of experimental data, approximate expressions

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Symbols

B	distance between the inner edges of nozzle exits.
t	nozzle thickness at exit.
θ	jet discharge angle measured from horizontal at nozzle exit.
S	base area enclosed by inner edge of nozzle exit.
S_j	total sectional area of nozzle exit.
h	hover-height.
$x=$	$t(1+\cos\theta)/h$
Q	volume flow rate of air.
$\bar{V}_j$	mean jet velocity at nozzle exit. ($\bar{V}_j=Q/S_j$)
ρ	density of air.
μ	viscosity of air.
ν	kinematic viscosity of air.
$J=$	$\rho S_j \bar{V}_j^2$
$q_j^*=$	$\rho \bar{V}_j^2/2$
L	total lift.
Δp	mean cushion pressure.
$\Delta p^*=$	$(L-J\sin\theta)/S$ (nominal cushion pressure)
H_j	mean total pressure of jet at nozzle exit.
C_p	pressure coefficient. ($C_p=\Delta p^*/q_j^*$)
C_H	total pressure coefficient ($C_H=H_j/q_j^*$)
C_L	total lift coefficient ($C_L=L/q_j^*S$)
$H_{req.}$	required total pressure of fan.
P_F	required fan shaft horse power.
C_{PF}	shaft horse power coefficient.
R_e	Reynolds' No. ($R_e=\bar{V}_j t/\nu$)
R	mean radius of curvature of jet.