대 한 조 선 학 회 논 문 집
제 42 권 제 2 호 2005 년 4 월

Journal of the Society of Naval Architects of Korea
Vol. 42, No. 2, pp. 80-87, April 2005

몰수 심도가 작은 고속 수중익 주위의 속도장 측정

김덕호*, 이정무*, 이승준† **

충남대학교 선박해양공학과 대학원*
충남대학교 선박해양공학과**

Measurement of Velocity Field Around Hydrofoil of Finite Span with Shallow Submergence

Deok-Ho Kim*, Jeong-Moo Lee* and Seung-Joon Lee† **

Graduate School, Dept. N.A.O.E., Chungnam National University*
Dept. N.A.O.E., Chungnam National University **

Abstract

A set of experiments was carried out for obtaining the velocity field around the hydrofoil of finite span, using a wing of the NACA 0012 section in a circulating water channel. DPIV technique was used to measure the velocity field, and the velocity measurements along the span were done for 3 speeds, 3 submerged depths, and 4 angles of attack. Experimental data are compared with the theoretical assumptions, as well as the numerical findings by Lee and Lee(2004). Special care is given to the flow near the tips and in the region close to the leading edge. Though indirect, using the measured data of the velocity, it is now possible to compare the aerodynamic and the hydrodynamic strength of the circulation distribution of a wing in the framework of the lifting-line theory.

※ Keywords: induced stream(유기유동), downwash(하향유동), Circulating Water Channel(CWC, 순환수조), Particle Image Velocimetry(영상 입자 속도 계측)

접수일: 2004 년 7 월 21 일, 승인일: 2004 년 12 월 15 일

†주저자, E-mail: sjoonlee@cnu.ac.kr
Tel: 042-821-6627

1. INTRODUCTION

In Prandtl's lifting-line theory, an integro-differential equation for the sectional circulation C_l corrected for the downwash w induced by the trailing vortex sheet plays a central role. Following the similar line of thought Wu(1954) proposed a lifting-line theory for hydrofoils of finite span, and obtained the following integro-differential equation for C_l corrected for the induced stream u, which is in the opposite direction of drag, as well as the downwash,

$$C_l = 2\pi\{\alpha(1-u)-w\} \qquad (1)$$

where α is the angle of attack.

In survey of the previous experimental findings at NACA, Wu quoted that at depths larger than four chords, the influence of the free surface is negligibly small, and that in the range of depths between four chords and a half chord lift and drag coefficients are reduced as the submerged depth. And the corresponding value of the lift to drag ratio increases to a maximum as the depth decreases until the hydrofoil breaks through the surface, and with the further decrease in depth it decreases very rapidly and eventually to that of the planning surface.

Parkin et al.(1956) measured the pressure distribution on two geometrically similar Joukowski hydrofoils and reached a conclusion that even at the shallow submergences the principles of potential theory might be expected to lead to valid and useful results for high speeds. They made a distinction between the two flow regimes, namely the high Froude number, Fn, and the low Fn, where the Fn was defined as $U/\sqrt{gc}$. Here, U is the speed of the hydrofoil or that of the incoming uniform stream, g the acceleration due to gravity, and c the chord of the hydrofoil. They tested for 2 depths, which were a quarter and a fifth chord, and in the range of depths they tested, the critical value of Fn for dividing the two regimes was observed as 0.61. For Froude numbers higher than this the flow was more like that of deeply submerged hydrofoils, however, on the contrary for Froude numbers lower than this it changed markedly, and the hydraulic jump occurred and even the Kutta condition was not satisfied at the trailing edge They also showed that the important dimensionless parameters for studying the flow around the hydrofoil running near the water surface were Fn, α, and the depth ratio, ie the ratio of the submerged depth h and c. In the present work, h is the vertical distance measured from the leading edge to the water surface.

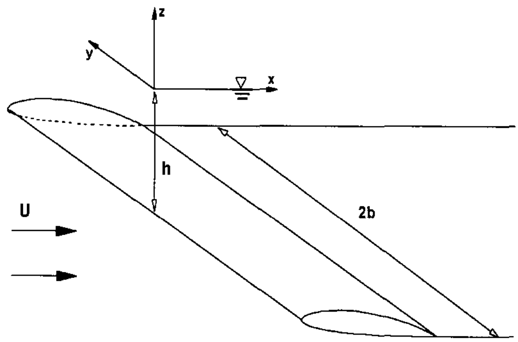

Fig. 1 The co-ordinate system and a schematic diagram

The co-ordinate system and a schematic diagram of the problem under consideration are shown in Fig. 1, and the half span of the hydrofoil is denoted as b. Although the spanwise elliptical distribution of circulation is seldom adopted for practical use, it is an important case since for a wing in an unbounded medium it corresponds to a constant downwash along the span, and also to the optimum value of the lift to drag ratio. For hydrofoils near the water surface, Wu(1954) also made use of the elliptical distribution of circulation. However, it is not well known that how large is the magnitude of the induced stream and the downwash, and their variation along the span of hydrofoils of general plan form.

Most of previous experimental works on hydrofoils were related to the lift and drag, the wake survey, the location and the structure of tip vortices, pressure distributions, and surface elevations, and it is hard to find works on the measurement of the velocity distribution near the leading edge. Hence the start of this work, and the current paper is the first report on the ongoing efforts of our laboratory.

2. EXPERIMENTAL SETUP

All the experiments reported here were carried out with the CWC at the Chungnam National University. Test section of the CWC is 0.6m wide, 0.8m deep and 2m long. The maximum flow velocity is 1.8m/s, however, for its uniformity over the longitudinal and transverse cross sections it is usual to keep the velocity below 1m/s. More details on the CWC and the experimental setup can be found in Kim(2005). NACA 0012 section was chosen for the hydrofoil, which has the rectangular plan form and whose chord is 8cm, and span 24cm, so that the aspect ratio is 3. Magnitudes of the chord and the span were determined considering the size of the test section, the upper limit of the flow speed, and the accuracy of the measurements. Accordingly, the aspect ratio was not as large as desired, and it is hoped that the comparison sheds a light on the basic understanding of the flow field around the foil of finite span.

Velocity measurements were done using a set of digital PIV system, which consisted of a laser source, optical device for making a laser sheet, a high speed video camera system, and a PIV S/W and a P/C for handling the whole system and the data. The laser source was made by LEXEL, and its light intensity was 1.2 watts, which was rather weak. High speed video camera system was supplied by PHOTRON, and its model name was FASTCAM-X1280PCI. The PIV S/W was Thinker's EYES 2D, a make of Tientech Co.. For visualizing the flow, poly vinyl chloride seed of specific weight 1.020 made by Yakuri Pure Chemical Co. was used. The camera could take 500 frames per second, and each frame had 1024(vertical) by 1280(horizontal) pixels.

For each case of experiments, namely for a chosen speed of incoming flow, an angle of attack, and a submerged depth, velocities near the leading edge were measured at five longitudinal sections, which were the midspan both tips and the middle of the midspan and the tips. For each section pictures were taken for two seconds, and since the velocity at the leading edge could not be directly measured due to the strong reflection of the wing body, in order to obtain the value of the induced stream and the downwash there an extrapolation method using the least square fit was employed. For the least square fit data of 4 points were used, and the maximum distance of the nearest data point from the leading edge was 2.5mm. Velocity measurements were done for four angles of attack, namely $\alpha = 0°$, $3°$, $6°$, $9°$, for three representative speeds which were

0.3m/s, 0.6 m/s, 0.85m/s, and for three submerged depths, ie $h=$ 1.5cm, 7.5cm, 13.5cm, and the corresponding depth ratios were 0.19, 0.94, and 1.69, respectively. In order to hold the wing firmly in its intended inclined positions at different angles of attack, four adaptors were prepared connecting the quarter point of the midspan of the wing and the model-holding system attached to the channel, however, due to the existence of this rod the flow field around the midspan was inevitably disturbed. Since it was not practically possible to get the exactly same velocity for the same setting of the rpm of the driving motor, there were some differences between the real speed and the representative value. Altogether tests were done for 36 different cases, and each case needed measurement at 5 sections, therefore totally 180 sectional data sets were obtained for analysis. Reynolds number corresponding to the typical speed 0.6m/s was 4.2×10^4, and hence the flow could be regarded in general as laminar.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

As described above, velocities near the leading edge were measured for 36 cases, for which the measured Fn is given in Table 1. Using the representative velocities, we obtain the corresponding representative Fn's as 0.34, 0.68, 0.96. Lee and Kim(1996) proposed a criteria for wave breaking behind a shallowly submerged hydrofoil, and in Fig. 2 their criteria are shown with the current experimental cases along with experimental results of Parkin et al (1956). According to Lee & Kim's proposal wave breaking is not observable for cases C, D, G, H and I and indeed it was not observed for those cases,though for larger angles of attack it occurred for the case C. It is interesting to note that for the case C, when the angle of attack was smaller namely zero or $3°$, no wave breaking was observed, however, when it became larger namely $6°$ or $9°$ the wave

Table 1 Froude number of tested cases

h/c	0.19				
A	case	0°	3°	6°	9°
Fn	A	0.30	0.29	0.27	0.35
	B	0.66	0.66	0.68	0.59
	C	0.92	1.00	0.94	1.00
h/c	0.94				
A	case	0°	3°	6°	9°
Fn	D	0.31	0.34	0.32	0.29
	E	0.66	0.66	0.65	0.58
	F	1.00	1.00	1.00	1.00
h/c	1.69				
A	case	0°	3°	6°	9°
Fn	G	0.32	0.28	0.28	0.30
	H	0.66	0.65	0.64	0.66
	I	0.93	0.94	0.98	0.97

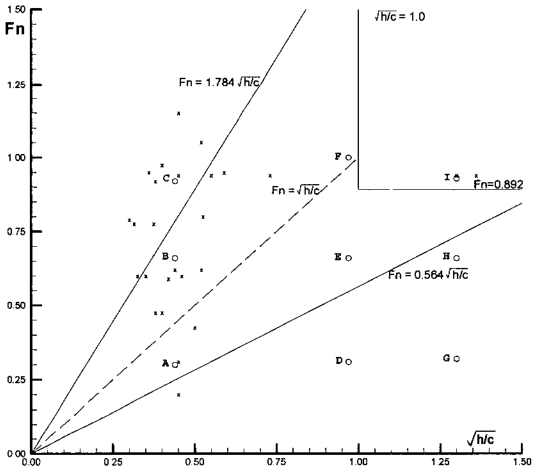

Fig. 2 A criteria for wave breaking

breaking occurred. Furthermore, it should be noted that their criteria were supposed to be valid for the two-dimensional foil, while in the current experiment a wing of the finite aspect ratio was used. The remark on the critical Fn by Parkin et al. (1956) was obtained for a fixed angle of attack $5°$, and hence the value of their critical Fn should be reduced when the wave breaking for smaller angles of attack is considered. Although the velocity was measured for 5 symmetrically placed sections, due to the asymmetry of the incoming flow and other possible experimental inaccuracies, extrapolated data were averaged to yield symmetric results.

In Fig. 3, shown is the effect of angle of attack for the case D(the representative Fn 0.34, the depth ratio 0.94, and the wave breaking absent), upon the induced stream and the downwash. It is clearly seen that as the angle of attack increases, the induced stream decreases, while the downwash increases. For the whole range of span the magnitude of the induced stream is larger or

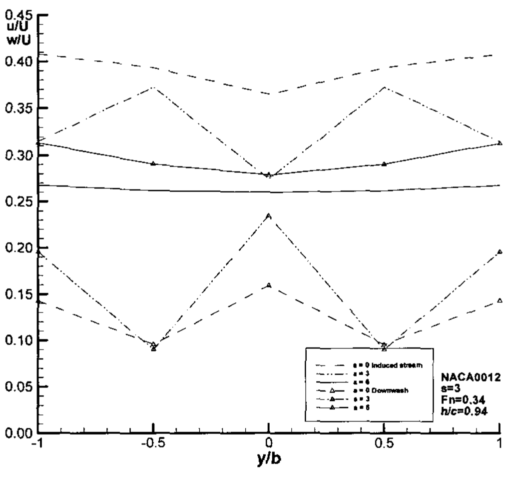

Fig. 3 Effect of angle of attack on induced stream and downwash for case D

comparable to that of the downwash. And the magnitude of the two induced velocities is surprisingly large, and this is probably due to the fact that the aspect ratio of the wing used in the experiment equal to 3 is rather small. The magnitude and the tendency of the change are all in general coincided with the finding of Lee and Lee(2004) by numerical computations, though the large Fn assumption was employed in the numerical coding. As the reduction of the induced stream contributes to the increase of the sectional lift and in turn to the lift of the whole wing, reduction of the induced stream with the angle of attack can be more or less expected. Furthermore, as the angle of attack gets larger the trailing vortices become more enhanced, and hence the qualitative behavior of the downwash is also anticipated. In Fig. 4 the same set for the case C(the representative Fn 0.96, and the depth ratio 0.19) is shown, and for this case wave breaking occurred for larger angles of attack. Thus as wave breaking sets in with the increase of the angle of attack the induced stream increases and the downwash decreases abruptly. In this regard, it is worth to emphasize that the effect of wave breaking changes the behavior of the flow field so drastically that without giving a due attention to the phenomenon of wave breaking it is very hard to draw any reasonable conclusion from the experimental data.

In Fig. 5 the induced stream and the downwash are shown for a fixed representative Fn being 0.34, for the case A D and G with the fixed angle of attack $3°$. In the case A wave breaking occurred and thus if only the case D and G are compared, it is clear that the induced stream decreases and the downwash increases as the submerged

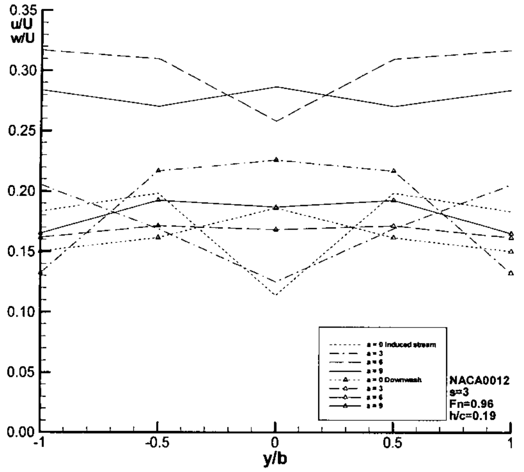

Fig. 4 Effect of angle of attack on induced stream and downwash for case C

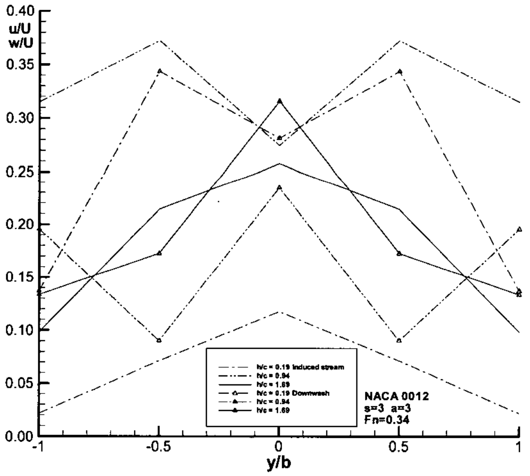

Fig. 5 Effect of submerged depth on induced stream and downwash(A, D, G)

depth gets larger. Again, this trend is in accordance with the finding of Lee and Lee (2004).

They also found out that the behavior of the flow field is reversed with the critical value of the depth ratio 0.5.

In Fig. 6 the same set for the case B, E and H is shown. For this set, the representative

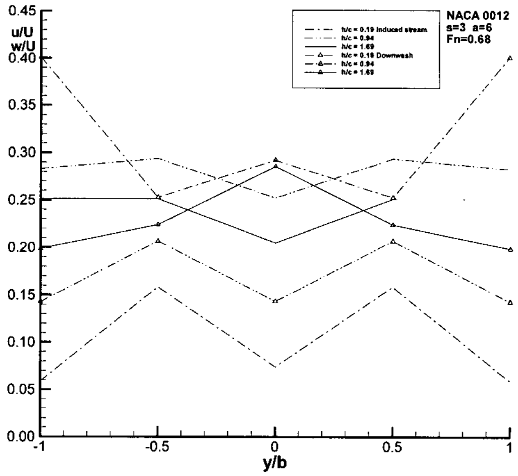

Fig. 6 Effect of submerged depth on induced stream and downwash(B, E, H)

Fn is 0.68, and the angle of attack is $6°$. We again note that for cases B and E the wave breaking occurred, while for H did not. Excluding the case H, we are led to the same conclusion as above.

In Fig. 7, the case A, B and C are shown, for which the depth ratio was 0.19 and the angle of attack was $6°$. Although wave breaking was present for all three cases, it is seen that the induced stream increases while the downwash decreases as the Fn gets larger. Also shown is the numerical prediction of the induced stream and the downwash, and it is observed that the agreement is remarkable even though the wave breaking is present for all three cases. In Fig. 8, the same set for the case G, H and I for the angle of attack $9°$ is shown. For these cases there was no wave breaking and the changing pattern of the induced velocities is not monotonic. However, the numerical prediction is on the right side of the experimental values, namely on the side of the increasing Fn .

Since Wu(1954) made use of the elliptical

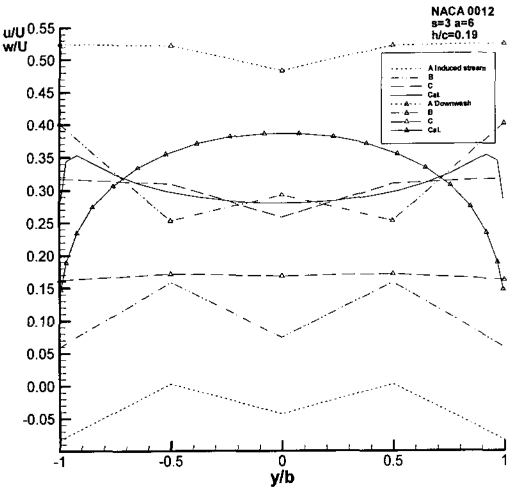

Fig. 7 Effect of Froude number on induced stream and downwash(A, B, C)

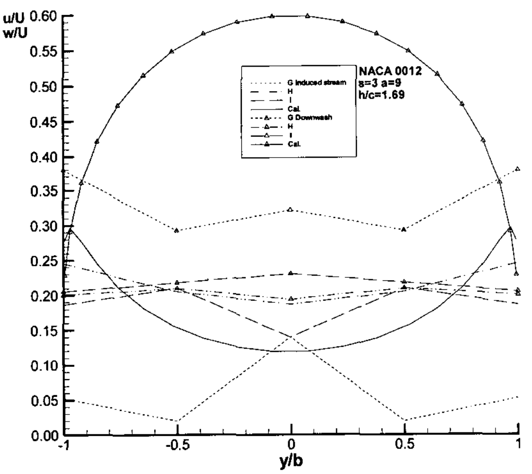

Fig. 8 Effect of Froude number on induced stream and downwash(G, H, I)

distribution of the sectional circulation, which in turn corresponds to the plan form of an ellipse, it is hard to make a direct comparison between the theoretical results obtained by him and the present experimental result. However, through the current experiments and the numerical simulations by Lee and Lee(2004), it was confirmed that the magnitude of the induced stream itself is not negligibly small and that the spanwise change of the induced stream and the downwash is not small either. Further numerical study is undergoing to make the direct comparison possible, and more physical and numerical experiments with the elliptic plan form is also being planned.

4. CONCLUSIONS

Although the aspect ratio of the tested wing was rather small due to the limits imposed by the experimental facilities, and sources of error in the measurement were present, we are led to the following conclusions.

First of all, the phenomenon of wave breaking affects the velocity field significantly, and experiment should be well designed taking into account its occurrence in advance Increasing the angle of attack or the submerged depth while keeping other parameters fixed, the induced stream decreases, while the downwash increases. On the other hand as the Froude number increases while keeping other parameters fixed, the induced stream gets larger, while the downwash becomes less. Of course, this interpretation should also be received with the due attention to the occurrence of the wave breaking.

Numerical findings and predictions are in general good agreement with the current experimental data.

For more direct comparison with the numerical prediction, a numerical code capable of representing the finite Froude number effect is being developed, and a set of experiments is planned using a wing of an elliptic plan form for more systematically varied submerged depths and the speeds.

ACKNOWLEDGMENTS

This work was in part sponsored by the Korea Science and Engineering Foundation(KOSEF) under the contract number R05-2002-000-00695-0, and we would like to express our sincere thanks to the KOSEF

REFERENCES

- Kim, D.H., 2005, Experimental study on the flow around hydrofoil of finite span with shallow submergence, MS Thesis of Dept. of NAOE, CNU(in preparation).
- Lee, J.M., and Lee, S.J., 2004, " Numerical study on flow field around high speed hydrofoil with shallow submergence," J. of Society of Naval Architects of Korea, Vol. 41, No. 5, pp. 8-13(in Korean).
- Lee, S.J. and Kim, H.T., 1996, " Lift of and wave breaking behind a moving submerged body with shallow submergence, " J. of Hydrospace Technology, Vol. 2. No. 1, pp. 1-9.
- Parkin, B.R., Perry, B. and Wu, Y.T., 1956, " Pressure distribution on a hydrofoil running near the water surface," J. of Applied Physics, Vol. 27, No. 3, pp. 232-240.
- Wu, Y.T., 1954, " A theory for hydrofoils of finite span," J. of Mathematics and Physics, Vol. 33, No. 3, pp. 207-248.


< 김 덕 호 >


< 이 정 무 >


< 이 승 준 >