J. Fluid Mech. (1973), *vol.* 61, *part* 1, *pp.* 85–96
Printed in Great Britain

An examination of the influence of waves on the ventilation of surface-piercing struts

By R. C. McGREGOR, A. J. WRIGHT, P. D. SWALES
Department of Mechanical Engineering, University of Leeds

AND G. D. CRAPPER
Department of Applied Mathematical Studies, University of Leeds†

(Received 10 May 1973)

The paper examines the results of an experiment which was designed to elucidate the manner in which wave characteristics, strut geometry and aspect ratio influence the angles at which struts ventilate. The experiment was conducted using small-scale models in a towing tank which allowed the wave parameters to be varied independently. The results indicate which parameters of a seaway are most hazardous to the operation of a hydrofoil ship in high seas and suggest design features which may extend the capability range of such craft.

1. Introduction

The hydrofoil craft was conceived near the end of the last century and many of its pioneers, including Wilbur and Orville Wright, were also associated with the aeroplane. Both inventions became practical realities at around the same time. There is some confusion as to which hydrofoil can claim the first flight, since some of the earliest boats should more properly be designated as hydroplanes (their foils act as planing surfaces at high speeds), but Forlanini's success on Lake Maggiore in 1906 is well documented. Since then, however, the rates of development of the two means of transport have been dramatically different. Passenger-carrying hydrofoils are restricted to comparatively short journeys over fairly sheltered waters and only a relatively few military prototype vessels such as the Canadian *Bras d'Or* have been proven in open sea conditions (Eames & Drummond 1972). Neither has there been an increase in speed since the modern military vessels have only just exceeded 60 knots, matching the speed reached by the Bell & Baldwin HD-4 in 1919; passenger craft seldom travel faster than 35 knots, which is similar to Forlanini's speed.

The modest exploitation of the hydrofoil compared with the airfoil is only partly a result of the respective needs for the two craft and the consequent research and production efforts. The complexities of a free surface and the phenomenon of liquid cavitation combine to produce a whole series of problems any one of which can be compared in complexity to the sound barrier in aerodynamics. Cavitation itself is a serious impediment to the development of hydrofoil craft beyond a speed of about 60 knots, but may be overcome by redesigning

---

† Present address: Department of Applied Mathematics and Theoretical Physics, University of Liverpool.

the foil system and accepting a lower lift-to-drag ratio. This means more costly travel and reduced range or payload. An obvious problem is that of surface waves. When their amplitude is significant in relation to the foil system, as occurs in open sea conditions, gross instability may result. A more subtle problem is that of ventilation, in which air is drawn down from above the free surface to explode in the low pressure regions of the struts and foils, causing loss of directional stability and foil lift. It can occur in a fraction of a second without warning at any speed, and with catastrophic results. Ventilation is liable to occur on all types of hydrofoil craft whether a fully submerged or a surface-piercing foil system is used, since it is inevitable that struts will pierce the surface. Consequently a proper understanding of the phenomenon is essential. Until recently the mechanism of ventilation inception has remained obscure, but work in the Mechanical Engineering Department of the University of Leeds under the sponsorship of the Canadian Government Defence Research Board has defined some of the ways in which it can occur in flat surface conditions (Swales, Wright, McGregor & Rothblum 1973).

Only one author (Kramer 1970) appears to have attempted to conduct experiments on the ventilation of a surface-piercing strut in a wave train. These experiments took place in the Lockheed Underwater Missiles Facility using four struts, of differing nose radius, which were similar in profile to a 12 % thick biogival section. Using only two attack angles, the ambient pressure was preset and the strut was accelerated gently through the velocity range in which ventilation inception was anticipated. This approach was necessary in a large facility where runs take an appreciable time and it is economically essential to obtain a data point on almost every run. Unfortunately, however, the method gives incremental velocity differences between successive wave crests, which is undesirable since the type of strut used is known to ventilate at different angles depending on the length of time suitable conditions prevail (Wright, McGregor & Swales 1973). Despite considerable scatter Kramer concluded that blunt struts were more resistant than sharp ones to the much earlier ventilation caused by the waves. Because of the ability to scale both Froude and cavitation numbers, quantitative suggestions were made for reductions in speed and angle relative to calm-water operating conditions for ventilation-free travel for particular specified wave and strut sizes. Kramer found that ventilation occurred at a crest in a head sea and at a trough in a following sea, and concluded that orbital velocity was the most important wave feature. From this it was proposed that cavitation number scaling ought to take into account the orbital velocity for comparison with the calm-water data. The residual scatter was still appreciable.

The work described in this paper is in no way a repetition of Kramer's work since its major objective is concerned with qualitative explanation based on experimental experience, rather than on the acquisition of model data which may be scaled for application to prototype design. The facility itself is dissimilar in concept and capability. Consequently the approach is radically different, each data point being determined from several runs with different attack angles rather than from one run with increasing speed. This approach leads to less scatter than that in Kramer's work.

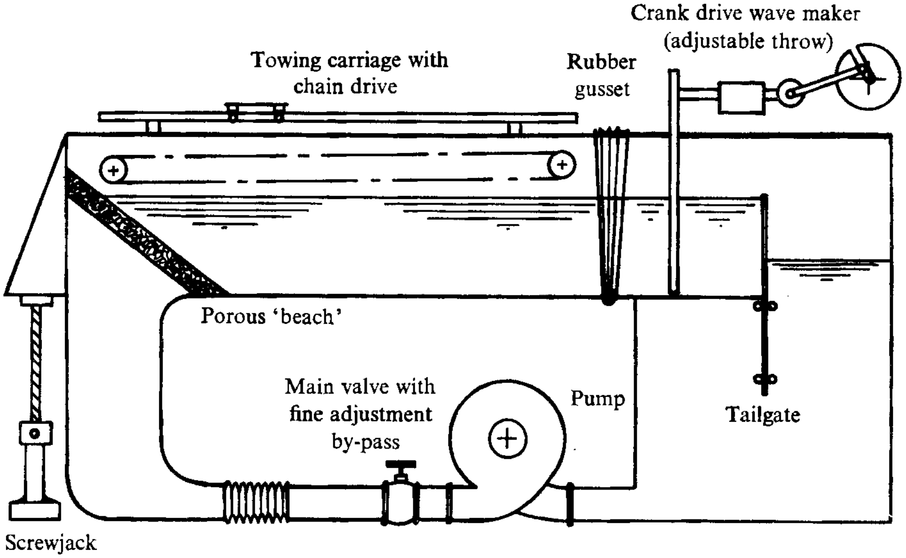

FIGURE 1. Schematic drawing of tank.

The results suggest that the steepness and accelerations of the waves are the most important features; and that the phase relationship found by Kramer does not hold for very steep following waves.

2. Experimental apparatus and procedure

The experiment was conducted in a new tank in the Department of Applied Mathematical Studies, Leeds University. Since the tank was designed primarily for the illustration of a wide variety of fluid flow problems to students taking theoretical courses in fluid dynamics, it has a greater flexibility than purpose-built experimental tanks of comparable size. A schematic drawing of the tank (figure 1) shows the main features. It is possible to use all the features simultaneously although slight modifications to the normal running procedure are required if it is necessary to operate the main pump with the wave maker and beach in place. In this experiment the jack and pump were not used.

The struts were mounted on the towing carriage, together with an angle indicator, three miniature 650 W lights and a mirror. The mirror was angled at 45° to the cine camera, which was mounted at the end of the tank at a point on the centre-line. This allowed the film record to show the image of a measuring tape which was attached to the inside of the towing-carriage running rail thus enabling the exact location and velocity of the strut to be established at any time during a run. The velocity was found to be constant over the filmed running length. The three lights, which had to be protected from splashing by Pyrex covers, provided sufficient illumination for monochrome cine film to be used at 200 frames/s.

Before each set of runs the amplitude a and the wavelength λ of the waves were measured photographically and the wave frequency f was counted. Wave makers of the piston type do not produce the correct velocity decay with depth and this can lead to cross-waves (Mahony 1972). Because of this and the residual reflexions, care was taken that the photographic measurements and the runs were made as soon as the wave train was fully established. The ventilation angle was taken to be the smallest angle for which ventilation occurred after the anomalous cases, when inception took place during the acceleration or deceleration of the carriage, had been eliminated. This angle was found from several runs with different attack angles in otherwise identical circumstances. Kramer (1970) and earlier work at Leeds have shown that inconsistent results can be caused by small imperfections in the strut profile, so the attack angle was always put on by turning the strut to port.

The test programme was restricted to four struts:

(*a*) a blunt-nosed biogival strut of aluminium bronze for which the nose radius-to-chord ratio r/l was 1 %, the thickness-to-chord ratio t/l was 10 % and the chord l was 0·1 m;

(*b*) a NACA 0012 aerofoil section of painted aluminium, $l = 0{\cdot}1$ m;

(*c*) foil (*b*) reversed, referred to as NACA 0012R, $l = 0{\cdot}1$ m;

(*d*) a brass 6° sharp wedge, $l = 0{\cdot}075$ m.

The biogival strut was tested in both head and following seas at aspect ratios, ratios of the submerged span to chord in undisturbed water, of 1·0 and 1·5. The remaining struts were tested for head seas at an aspect ratio of 1·5 only.

3. Results

The ventilation angle α is seen to be sensitive to the orbital velocity w as shown in figures 2 (*a*) and (*b*). In figure 2 (*a*) it can be seen that the gradient of the best straight line is the same for the four conditions under which the biogival strut was tested. In figure 2 (*b*), however, while a straight-line fit is still good, widely different gradients are necessary. The equation of such a line is

$$\alpha/\alpha_s = \exp\{-mw\} = \exp\{-2m\pi af\}, \tag{1}$$

where α_s is the angle of ventilation in still water. The gradient m is independent of aspect ratio and heading but is a function of strut shape. An expression of a form similar to

$$m \simeq 3000\,(r/l)^{-\frac{1}{4}}\,(t/l)^{-4}, \tag{2}$$

where r/l and t/l are percentages, may be appropriate. From results for only four struts equation (2) is to be considered as a suggestion rather than a proven empirical relation.

The dependence of the ventilation angle on the steepness ofthe wave (figures 3 *a*, *b*) is similar in many respects to the orbital velocity graphs. The different conditions shown in figure 3 (*a*) for the biogival strut are best represented by four nearly parallel lines, whereas the ratios ot the gradients of the best lines in figure 3 (*b*) are similar to those in figure 2 (*b*). The curves may be expressed by

$$\alpha/\alpha_s = \exp\{-3{\cdot}05m\delta\}, \tag{3}$$

where $\delta = 2a/\lambda$ is the wave steepness.

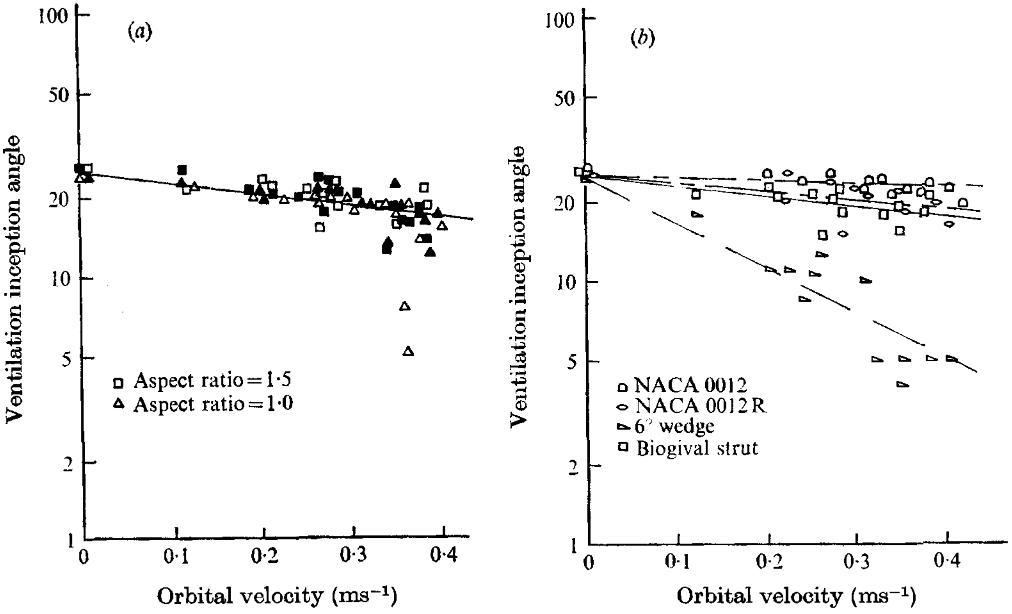

FIGURE 2. Ventilation angle against orbital velocity. (*a*) Blunt biogival strut in head (open symbols) and following waves (solid symbols). (*b*) In head waves at an aspect ratio of 1·5.

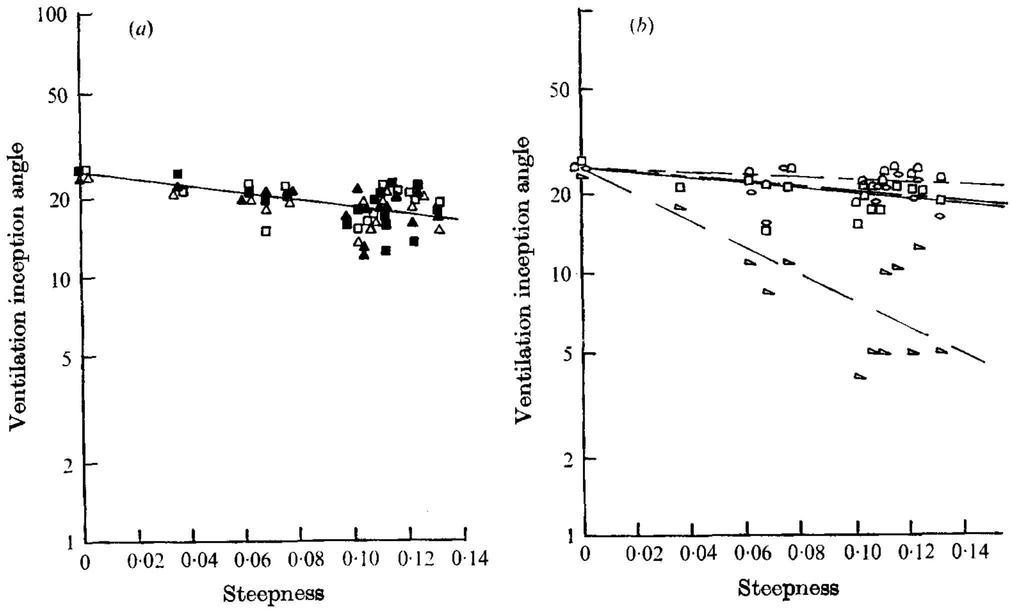

FIGURE 3. Ventilation angle against steepness. (*a*) Blunt biogival strut in head and following waves. (*b*) In head waves at an aspect ratio of 1·5. Notation as in figure 2.

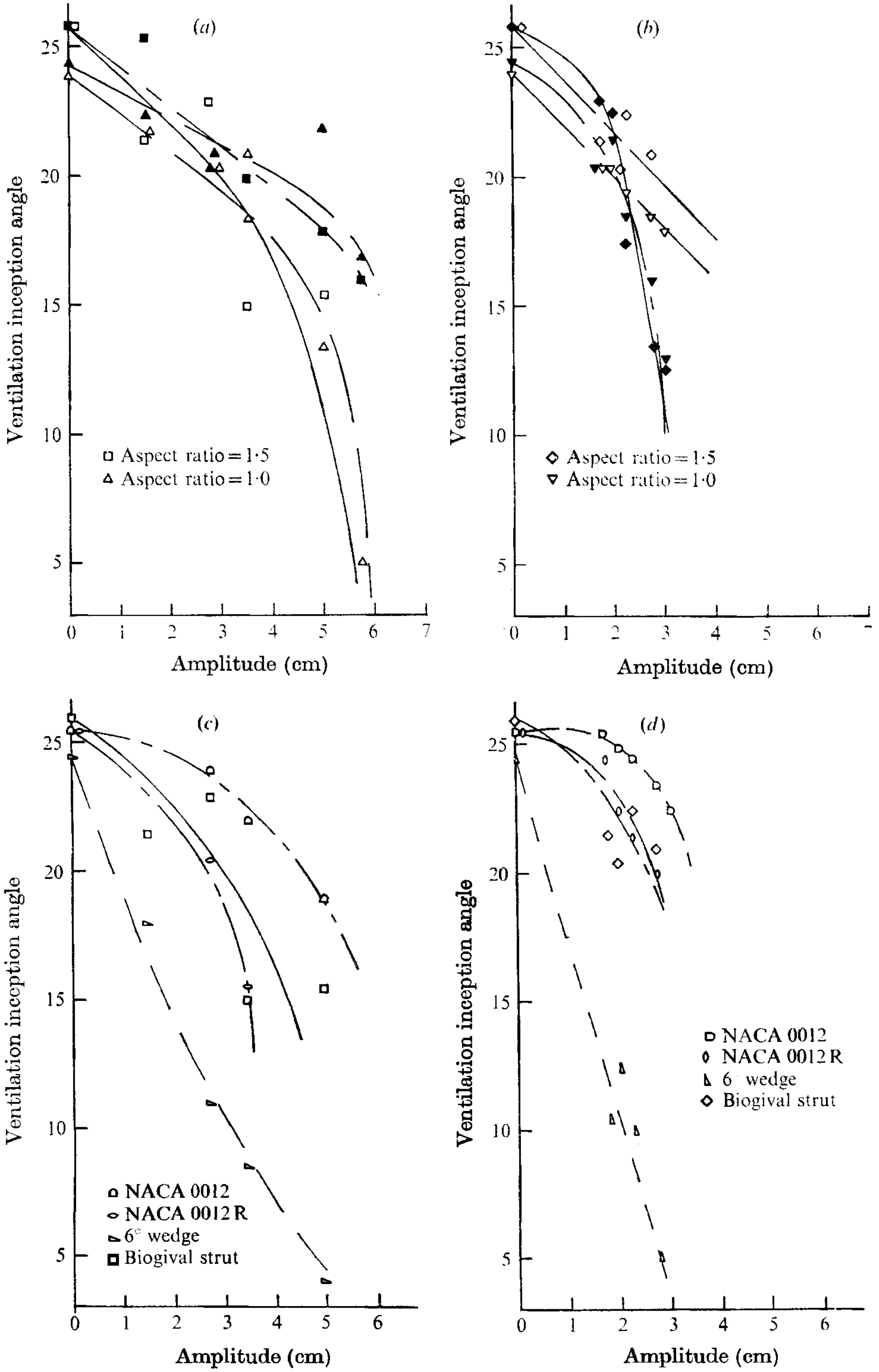

FIGURE 4. Ventilation angle against amplitude. (*a*) Biogival strut in head (open symbols) and following waves (solid symbols) of frequency 2·2 Hz. (*b*) Biogival strut in head (open symbols) and following waves (solid symbols) of frequency 1·1 Hz. (*c*) In head waves of frequency 2·2 Hz at an aspect ratio of 1·5. (*d*) In head waves of frequency 1·1 Hz at an aspect ratio of 1·5.

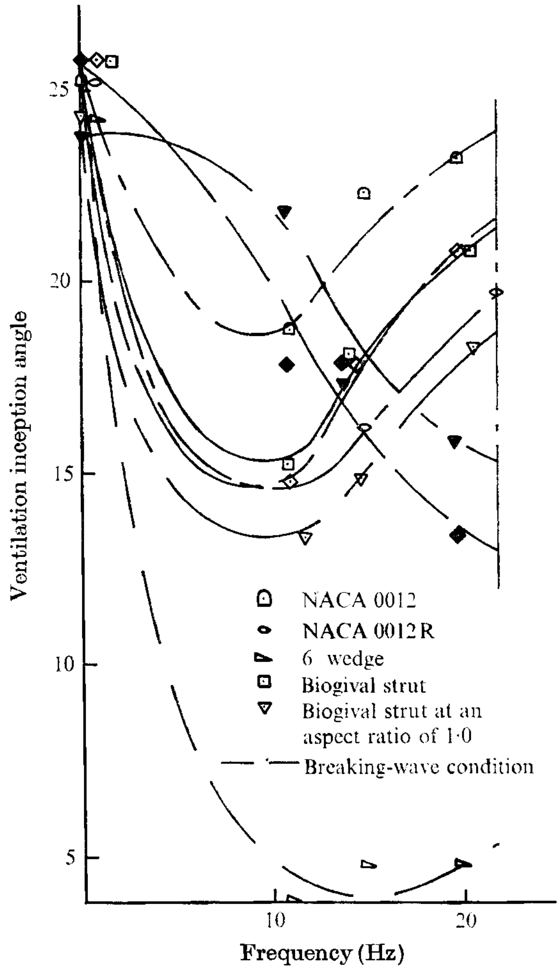

FIGURE 5. Ventilation angle against frequency in head (open symbols) and following waves (solid symbols) of amplitude 5 cm. Aspect ratio = 1·5.

The behaviour of the ventilation angle with amplitude for waves of a particular frequency is illustrated in figures 4 (*a*)–(*d*). It is clear again that the aspect ratio is of little importance but that the heading makes a considerable difference. At the highest frequency used the ventilation phenomenon is less sensitive to a following sea but at the other end of the frequency range the position is reversed. In fact the results for a head sea are not much affected by frequency changes but those for a following sea are very sensitive to them. The intermediate frequencies confirm that this is a genuine trend.

Figure 5 shows that there is a particular wave which minimizes the ventilation angle. The frequency of this wave is dependent on amplitude and heading but not influenced greatly by strut profile or aspect ratio. In a head sea the critical frequency decreases steadily as the amplitude is increased whereas in a following sea the amplitude has little effect until it is quite large.

The analysis of the cine film showed that ventilation took place at or very near the wave crest for all conditions tested, including the following-sea tests. When the wave frequency was 1·1 Hz the velocity of the crest in a following sea and the velocity of the towing carriage were similar and a wide range of angles existed where ventilation could occur, depending on which parts of the wave cycle were experienced by the strut. The angle which defined the boundary between vented and wetted flow was the lowest angle at which ventilation was observed, when the wave phase was most favourable to ventilation inception.

4. Discussion

In previous work by Kramer (1970) it was found that ventilation occurred at a crest in a head sea and near the trough, although with considerable scatter, in a following sea. On the strength of this phase relationship the orbital velocity was selected as the most important wave parameter. The use of a local cavitation number improved the agreement with calm-water results although this was debatable in the case of a following sea.

In the light of those conclusions our observation that ventilation occurred most readily at a crest in a following sea was unexpected. However, in this experiment, which was conducted at low speed, it would have been equally surprising if changes in velocity of at most 0·43 ms^{-1} had been responsible for the drastic reduction in inception angles reported, since in the cases of the NACA 0012 and the blunt biogival struts the ventilation inception angle is insensitive to speed in this range (Swales, Wright, McGregor & Cole 1973). For a small amplitude wave the orbital velocity $(\dot{x}, \dot{y})$ may be expressed in Cartesian co-ordinates, with Ox horizontal and Oy vertical, by

$$\dot{x} = 2\pi af \frac{\cosh\{2\pi(y+h)/\lambda\}}{\sinh 2\pi h/\lambda} \sin\{2\pi(x/\lambda - ft)\} \tag{4}$$

and

$$\dot{y} = -2\pi af \frac{\sinh\{2\pi(y+h)/\lambda\}}{\sinh 2\pi h/\lambda} \cos\{2\pi(x/\lambda - ft)\}, \tag{5}$$

where a is the amplitude, f is the frequency as seen by a stationary observer, λ is the wavelength of the wave and h is the water depth. This means that the local horizontal velocity u varies in the range

$$U - 2\pi af \leqslant u \leqslant U + 2\pi af, \tag{6}$$

where U is the strut speed. The ventilation point in these tests corresponds to the maximum value in a head sea and a minimum in a following sea. This suggests that if it is the orbital velocity which is important then it must be the vertical component $\dot{y}$, which is bounded by

$$|\dot{y}| \leqslant 2\pi af, \tag{7}$$

which matters. The reason why the dependence on steepness δ (figure 3) is similar to that on orbital velocity (figure 2) is seen by writing

$$\delta = \frac{2a}{\lambda} = \frac{4\pi af^2}{g} = \frac{2fw}{g}. \tag{8}$$

Taking the mean value of the frequencies used in the experiments, the coefficient of w is $1/3{\cdot}05$, giving an equivalence between equations (1) and (3). This may be justified since the experimental frequency range was necessarily restricted by the facility and the direct dependence on frequency was not great compared with that on the amplitude.

Throughout this experiment ventilation was seen to occur when the steepness of the wave was enhancing the discrepancy in water levels between the leading and trailing edges which exists because of the pressure distribution round the strut. When ventilation occurs as the nose of the strut intersects the crest, which was the most common case, the tail of the strut experiences a vertical velocity of opposite sign for the different headings. Near the crest the vertical velocity is small in relation to its maximum and it is therefore concluded that under the conditions covered by the present tests the orbital velocity itself does not provide an adequate mechanism to explain the premature ventilation inception experienced.

Returning to consideration of the factors liable to influence ventilation in a wave train, the duration of the existence of suitable conditions can be dismissed since at the speed tested some of the struts are known to have only slight time dependency (Wright *et al.* 1973). The series with the biogival strut at a smaller aspect ratio shows that the change in aspect ratio due to the passage of the wave is not important. Nor is the rate of change of aspect ratio since this is proportional to the vertical velocity, which has already been shown to be unable to provide a mechanism for ventilation consistent with observation. Since the velocity, the acceleration and the steepness all depend linearly on the amplitude for small waves it is clear that the amplitude is more important than the frequency in influencing ventilation. Remembering that the wave frequency experienced by the strut varies a great deal from the set frequency because of the widely different relative velocity between the strut and the wave crest, the frequency seems to have a very small role.

From these results and deductions it is possible to suggest the manner in which ventilation occurs in a wave train. First, the water surface is covered by many more small-scale disturbances than in nominally flat test conditions. These disturbances may be the capillary waves which ride on the forward faces of gravity waves (Longuet-Higgins 1963; Crapper 1970) or waves caused by the wave-induced vibrations of the foil itself. It was shown in Wright, Swales & McGregor (1972) that surface perturbations close to the strut grow rapidly as they travel along the chord. These waves are apparently associated with the high downward acceleration of the surface which is caused by the low pressure regions which exist on the foil. Near a crest the increased aspect ratio causes the surface and tip vortex effects to become smaller allowing lower pressures to exist on the foil. This contributes to the surface accelerations, which are further enhanced by the wave acceleration itself. Taking into account gravity, surface tension and the imposed downward acceleration, designated $-ng$, where n is a numerical factor, Bernoulli's equation may be written as

$$\frac{\partial\phi}{\partial t}-\frac{T}{\rho}\frac{\partial^2\eta}{\partial x^2}-(n-1)g\eta = 0 \quad \text{on} \quad y=0, \tag{9}$$

where ϕ is the velocity potential, T is the surface tension and $y = \eta(x,t)$ is the free surface. The frequency f_c of such waves is given by

$$f_c^2 = \frac{1}{2\pi\lambda_c} \tanh\left(\frac{2\pi h}{\lambda_c}\right)\left(\frac{4\pi^2 T}{\rho\lambda_c^2} - (n-1)g\right), \tag{10}$$

where λ_c is their wavelength. Consequently waves are unstable if

$$\lambda_c > 2\pi[T/\rho(n-1)g]^{\frac{1}{2}}. \tag{11}$$

If d is the surface drop along the chord of the foil in calm water the order of magnitude of the necessary downward acceleration a_s may be estimated by assuming it to be uniform as

$$a_s \sim 2u^2 d/l, \tag{12}$$

where l is the chord length. At the test speed, a typical calm-water figure for d/l is approximately 0·5 (Swales, Wright, McGregor & Rothblum 1973), which gives $n \simeq -2{\cdot}5$. Thus from (10) all waves longer than 0·014 m will grow. In waves there is a contribution to n at a crest from the downward acceleration a_w due to the wave. This acceleration is bounded by

$$|a_w| \leqslant g\pi\delta = 30{\cdot}8\delta, \tag{13}$$

for small waves. Conditions at a crest for either heading are such that the acceleration is near its maximum numerical value in the downward direction. (Figures 3(*a*) and (*b*) may be regarded as plotted against acceleration if the abscissa co-ordinate is multiplied by 30·8.) This expression, from small amplitude wave theory, underestimates the downward acceleration of the highest gravity wave by 12 % (Longuet-Higgins 1963). It follows, from (10), that near to a crest in steep waves the capillary waves become unstable when 20 % shorter than in calm water. Near the troughs of waves slightly longer wavelengths are stable.

From Longuet-Higgins (1963) and Crapper (1970), the wavelength of the linearized capillary waves generated by a gravity wave is $2\pi T/\rho V^2$, where V is the velocity of the stream and may be approximated by

$$V = c(1 + A^2 - 2A\cos m\phi)^{\frac{1}{6}}, \tag{14}$$

where c is the phase velocity, A is a steepness parameter which has a maximum value of unity for the steepest wave and $\phi = \pm\pi/m$ are the troughs adjacent to the crest at $\phi = 0$. From these expressions it is clear that waves which are potentially unstable are generated over the part of the forward faces of gravity waves for which

$$(1 + A^2 - 2A\cos m\phi) < [(n-1)gT/\rho c^4]^{\frac{2}{3}}. \tag{15}$$

This inequality has a real solution for ϕ provided that the wave is steep enough.

Let it be postulated that, for a given strut velocity relative to the water, a particular total downward acceleration is required before ventilation will occur. (Since acceleration and surface depression d along the chord are approximately linearly related, this is substantially the proposal of Swales, Wright, McGregor & Rothblum (1973).) Then since d is dependent on the angle of attack, it is clear that, in steep waves, a_w is a powerful influence not only for reducing the ventilation angles at a crest, by the additive method suggested, but also by generating a supply of capillary waves of appreciable amplitude on the forward faces of the gravity wave. These waves, which are stable on the gravity wave, are potentially unstable once exposed to the acceleration field of the strut itself, and because of their amplitude need less amplification before they break. Surface curvature also has an influence on perturbation growth near the crest of a gravity wave and it may be that the curvature induced along the chord by a_s may act in the same way near the trailing edge. The breaking of these waves near the trailing edge of the strut traps air in, and below, the surface layer of fluid and when the air level is high enough causes this surface seal to be explosively breached, creating a ventilated cavity (Wright *et al.* 1972). Since a gravity wave tends to peak at a crest and flatten in the trough, the acceleration a_w in the vicinity of a trough will be very much less than $+\frac{1}{2}g$. Thus, at a trough, a_w has only a very small inhibiting effect and this delaying factor may be more than compensated by the effect on a_s of the local increase in speed if the strut is in a regime where the ventilation angle is sensitive to speed changes.

In a seaway, however, the surface is covered by myriads of small waves and therefore it is no longer justified to associate the presence of large amplitude capillary waves exclusively with the wave crest as is clearly the case in a small towing tank. Also since the acceleration a_s increases with U in spite of the smaller values of d which are necessary before ventilation may be expected, the relative significance of a_w in reducing ventilation angles at a crest or inhibiting them at a trough becomes smaller at prototype speeds, all other things being equal. In this experiment the strut was fixed in the vertical plane corresponding to the situation of a strut on a platforming hydrofoil and consequently experiencing the full negative gravity effect of the wave. If, however, a hydrofoil contours or partially contours the wave effects will be reduced provided that the strut's motion is in phase, but if for any reason that part of the craft should be slightly out of phase the motion of the craft itself could catastrophically enhance the wave's influence.

5. Conclusions

Generalizing the results of this experiment it is clear that waves significantly reduce the ventilation inception angle for all foils. Although sharp struts ventilate more readily in waves than do blunter ones it is possible to compensate for this by making the foil thicker. Blunt thick struts are the least sensitive to wave-induced ventilation. The factors which most influence ventilation in steep waves are those related to the amplitude, particularly the vertical acceleration and the induced perturbations. In a head sea all the factors are favourable to ventilation at a crest but in a following sea the most favourable point of the wave varies, depending on wave steepness, and ventilation can occur at a trough in flatter waves. To avoid ventilation it is necessary to reduce the angle of attack in comparison with the calm-water figures but it is unrealistic to scale up tests such as these to ensure fully wetted flow when the basic flow is dependent on so many scaling factors. The application of cavitation number scaling as suggested by Kramer

(1970) is useless in very steep waves where ventilation occurs at a crest in the following waves because the necessary phase relationship has broken down. There is also no guarantee, because of the conflicting mechanisms, that the necessary phasing will appertain at sea.

From the results of these tests it is not possible to determine the influence of the decay of velocity with depth or the effective changes of profile caused by the vertical velocities. Both of these aspects would require an exhaustive experimental programme in a larger facility.

The authors are indebted to the Defence Research Establishment, Atlantic, Halifax, Nova Scotia, for financial support for this work.

REFERENCES

CRAPPER, G. D. 1970 Non-linear capillary waves generated by steep gravity waves. *J. Fluid Mech.* **40**, 149.

EAMES, M. C. & DRUMMOND, T. G. 1972 H.M.C.S. *Bras d'Or* sea trials and future prospects. *Proc. R.I.N.A.*

KRAMER, R. L. 1970 An experimental study of the effect of waves on ventilation of surface piercing struts. LMSC/DO 29678.

LONGUET-HIGGINS, M. S. 1963 The generation of capillary waves by steep gravity waves. *J. Fluid Mech.* **16**, 138.

MAHONY, J. J. 1972 Cross-waves. Part I. Theory. *J. Fluid Mech.* **52**, 229.

SWALES, P. D., WRIGHT, A. J., MCGREGOR, R. C. & COLE, B. N. 1973 Separation and ventilation studies on four foil shapes. (To be published.)

SWALES, P. D., WRIGHT, A. J., MCGREGOR, R. C. & ROTHBLUM, R. S. 1973 The mechanism of ventilation inception on surface piercing foils. (To be published.)

WRIGHT, A. J., MCGREGOR, R. C. & SWALES, P. D. 1973 Time dependency of ventilation. *Hoveringcraft & Hydrofoils*, **12**, 9.

WRIGHT, A. J., SWALES, P. D. & MCGREGOR, R. C. 1972 Ventilation inception on surface piercing foils or struts. *Nature*, **240**, 465.