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References


DISCUSSION

T. Y. Wu

My comment is stimulated extemporaneously by the interesting point just raised by our Session Chairman, Marshall Tulin, on possible application of the semi-empirical correction rule for improving the accuracy of linear theory. This correction rule was first introduced for a simple and effective evaluation of the error due to the camber and cavitation-number effects on the performance of a cavitating hydrofoil in unbounded flow. The overall correction of this rule, I believe, is in the direction, in general, of reducing the overprediction of the lift and drag coefficients by linear theory, at fixed cavitation number, as long as

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the predicted lift is positive. A very interesting feature of the present result obtained by Dr. Furuya, as I noticed, is that his predicted lift coefficient of a blade in cascade is not always smaller than the corresponding result of linear theory, there being a few cases where the opposite situation was found in contrast with the unbounded flow case. It therefore seems this problem would offer an interesting test case for further versatile application of the correction rule. I wonder if Dr. Furuya would agree with this view.

B. Yim

The author dealt with a very complicated and difficult problem. As in the case of the isolated foil, an important problem is to pick an appropriate first approximation. However, in the practical problem of predicting the cavity drag of a cascade in a supercavitating propeller, it may not be too difficult. Because normal propeller blades have small cambers, the first approximation should be flat-plate cascades. In the off-design problem, the angle of attack may be quite large. Thus, it is necessary to deal with them with a nonlinear method. However, it is relatively easy to solve for the flat plate cascades. For infinite cavities, it is a classical problem solved by Bets and Petersohn. Thus, a practical problem will be rather to solve for flat plate cascades first, with a simpler method, and to build a solution for cambered foils using the flat-plate solution.

For flat plate cascades, the constant $\hat{A}$ may be determined by first imposing a condition $T = 1$ in the potential plane. Then the actual scale will be found from the solution. This is possible because $\beta$ is constant on the flat-plate foil. For large stagger angles or for large solidities $\hat{A}$ is very large. This fact seems to give trouble especially when we want to find $\hat{A}$ with complicated equations.

Once the solution for the flat-plate cascade is found we may find the perturbation for the cambered foil relatively easily.

C. C. Hsu

The author considers the difficult, nonlinear problem of supercavitating flow past cascades. The choice of wake models in general have no serious consequence on the linearized results since the influences of wake are largely of higher order. This is not the case, however, in nonlinear analysis. This problem becomes more acute for cascades with high solidities and stagger angles in which the differences between neighboring blades and cavity wakes are considerable; in such cases the choice of realistic wake model (not just for convenience as contended by the author) is of paramount importance. The difference between linearized and nonlinear results generally decreases as the disturbances become smaller, such trend is not exhibited by the author's numerical calculations (for instance, see Fig. 11). Can the author provide some explanations?

J. O. Scherer

Dr. Furuya's nonlinear supercavitating cascade theory shows surprisingly strong nonlinear effects even for low angles of attack where we would expect linear theory to be adequate. Of particular interest is the pronounced influence of cascade solidity on lift and drag coefficients shown on Fig. 9 for a foil with 6 deg of incidence as compared to 8 deg. It is assumed that this is related to the change in cavity length with solidity shown on Fig. 10. However, the completely different trends shown on Fig. 9 for the 6 and 8 deg incidence angles is surprising considering that both have cavity lengths greater than one chord. Perhaps Dr. Furuya could comment on the physical cause for this result.

Author's Closure

I would like to thank all discussers for their various interesting comments. The author agrees with the comments made by Professor Wu that it would be very useful to have a simple correction rule for the present cascade problem. However, unlike unbounded flows, it is not quite clear how to handle geometric cascade features in approximate theories. These include solidity and stagger angle which play an essential role in generating nonlinear effects in this type of flow. The nonlinearity due to these factors has been clearly shown in Fig. 14 of the text, for example, even for small camber ($\alpha = 8$ deg) and the range of small cavitation numbers. Nevertheless, it would be very interesting to compare such a correction rule, if developed, with nonlinear theories as well as with experimental data.

The method proposed by Dr. Yim seems appropriate and versatile for design work where angle of attack and camber are relatively small. For the off-design conditions, however, the angle of attack is no more small. It is much simpler to use a nonlinear direct method from the beginning in such cases than to use an approximate flat-plate solution and to iterate the procedure. Dr. Yim also pointed out a technical difficulty in finding $\hat{A}$ in his inverse method in cases of large stagger angle and high solidity since $A$ becomes very large. We have not experienced any problems of that kind, but as mentioned in the text, had convergence problems for the coordinates $x$ and $\zeta$ which correspond to the end points of cavity. The author feels that both are essentially the same inherent problem in this type of analysis which uses a logarithmic mapping function.

Dr. Hsu's comments regarding the distinction between the importance of choice of wake model in linearized and nonlinear theories seem incorrect from a physical point of view. Regardless of theories applied, the choice of wake model is important for the problem of the cascades having high solidities and stagger angles due to the proximity of two blades. The accuracy of the presently used model has been well established in comparison with experimental data in an unbounded flow medium. However, final verification of use of the model in cascade flows at high solidities and stagger angles should await the comparison with experimental data which lacks presently. Further investigations in establishing new wake models to represent highly turbulent flow still remain an open area of interest. Another comment made by Dr. Hsu that the difference between linearized theories and nonlinear theories reduces as the disturbance becomes smaller is generally true. This kind of trend is quite significant in most cases as shown in the text except Fig. 11. It is to be reminded, however, that in this case the solidity, stagger angle and incidence angle are all small, 0.25 deg, 25.6 deg and 3.5 deg, respectively. Therefore, it is physically understood that the change of cavitation number or change in length and thickness of the cavity do not have much influence in the deference of two theories.

Mr. Scherer brought up a very interesting feature of supercavitating cascade flows that very strong nonlinearity of $C_{L}$ and $C_{D}$ as functions of solidity is shown in Fig. 9. As he pointed out, this can be understood by looking at a corresponding Fig. 9 showing the relation of length of cavity versus solidity. It shows that the cavity length for the case of $\alpha = 6$ deg reaches almost equal to one chord length at around solidity of 0.85 which agrees with the peculiar behavior of $C_{L}$ and $C_{D}$ in Fig. 9. This is a well known phenomenon in the cavity flow, found in any standard text book, that the force coefficients increase as the cavity length approaches one chord length. Whereas it is found that the cavity length was much larger than one chord for $\alpha = 8$ deg. I would like to emphasize again that this kind of strong nonlinear behavior is inherent in cascade flows and that it is essential for the designer to use a nonlinear theory.