NUMERICAL STUDY OF HIGH L/D OBLIQUE FLYING WING

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Abstract

The Oblique Flying Wing (OFW), which is a concept of the next generation SST, has the favorable characteristic of attaining a high L/D in a supersonic region. In this paper, OFW is defined by the local airfoil section, incidence distribution and bending. Sweepback angle and freestream mach number are taken into consideration as flight conditions. Some optimizations of the shape of the OFW and the flight conditions using the downhill simplex method are studied in order to demonstrate a high L/D or the ideal lift distribution in the span direction.

1 General Introduction

Today, the supersonic transporter (SST) has disappeared temporarily with the retirement of the Concorde. However, development of the next generation SST as a succession is rapidly being undertaken. OFW has some excellent features as a candidate of the next generation SST. The following are as some of these features.

- Weak shock wave reaching to the ground
- High *L/D* in a subsonic and supersonic region.

These features are produced from the simple body shape of the OFW and that should be noted as features that compensate for the flaws of the present SST. However, it is also due to this simple body shape that complicates the problem of flight stability, and this is pointed out as a flaw of the OFW.

In this paper, the high *L/D* characteristic in a supersonic region of the OFW are studied. Setting up a parameter about the body shape and flight conditions creates an OFW model. Optimization is performed on the model, using the downhill simplex method[2].

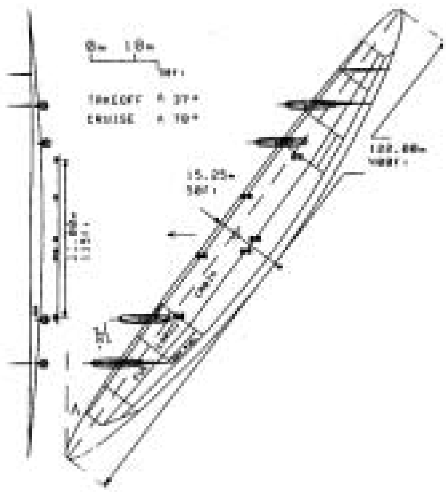

Fig.1. Oblique Flying Wing[1]

2 OFW Model

We use the following elements to define the model of the OFW.

- airfoil and incidence at each span station
- bending
- planform

We choose the method to determine the airfoil using 11 parameters. Incidence at each span station is given with non-linear distribution in the span direction. Bending is the perpendicular displacement at each span station and is set to the parabolic distribution. In this research, the two types of planform, symmetric and asymmetric, are considered. A simple example of the OFW shape is shown below.

In Fig.2, we see the OFW model with an asymmetric planform. In this figure, λ is the sweepback angle which is the parameter of the flight.

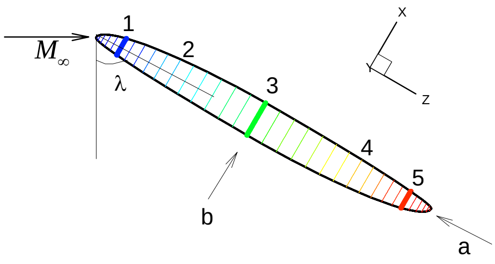

Fig.2. Oblique Flying Wing – planform

Fig.3 shows the airfoil and incidence changing according to the span station, and Fig.4 shows the parabolic distribution of the bending.

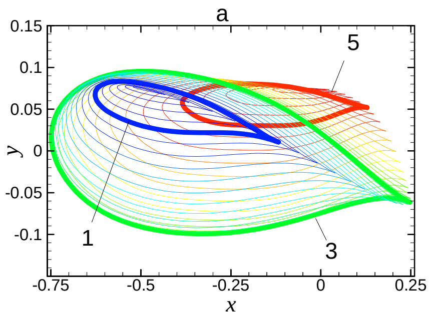

Fig.3. OFW- airfoil and incidence

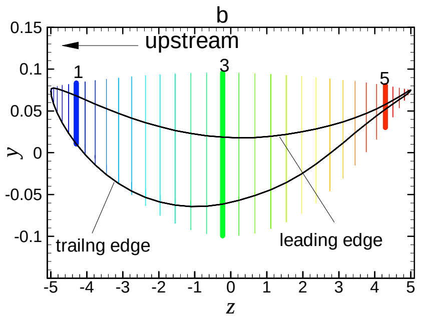

Fig.4. OFW- bending

3 Computational Method

3.1 Governing Equations and Numerical Scheme

In this study, supersonic viscid free stream is considered. However viscous effects are evaluated by the T' method[2]. Then the governing equations to be solved here are the three-dimensional Euler equations.

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+\frac{\partial G}{\partial z}=0 \qquad (1)$$

Yee's Up-wind TVD scheme is used for calculating the flux, and time integration is performed using the LU-SGS scheme.

3.2 Optimization Method

The downhill simplex method is used as the function minimization technique in the optimization. This method can change many parameters simultaneously aiming at the objective function minimum by a simple rule. The objective function, which should be made the minimum, is as follows when we want to attain only a maximized *L/D*.

$$G=-(L/D) \qquad (2)$$

3.3 Calculation Conditions

The coarse grid is used for optimization repetition calculation. After being completed by optimization calculation, a more exact OFW performance is checked by calculating the body shape and flight conditions, which were acquired by the optimization, using a fine grid.

The sweepback angle λ and free stream mach number M_∞ shown in Fig.2 are set as the flight conditions. As for the body shape parameters, several points in the span direction made into the control points are changed at optimization calculation, and at the other span station, the value of each parameter is set by spline interpolation. The number of optimization parameters which includes the sweepback angle, taking some airfoil definition restrictions into consideration, is about 35. The summary of the setup of each parameter is shown below.

Grid

- O-O type
- around the wing × spanwise × body-normal direction
  = 125×40×31 (fine grid)

= 53×31×26 (coarse grid)

Body shape parameters

- incidence : Set 5 control points in the span direction
- bending : Set the different $y_{bend\ max}$ at both ends of the span.
- airfoil : Set 11 parameters at three spanwise points.

Flight condition

- M_∞=1.2～2.2(1.2,1.4,1.6,1.8,2.0,2.2)
- λ (sweepback angle)

4 Results and Discussions

Some flight conditions (M_∞=1.2～2.2) are given, and the optimal body shape and sweepback angle at each speed are calculated. First, some optimizations are performed on the OFW with the asymmetric planform. And then the symmetric shape models of OFW are considered.

4.1 Optimization with Asymmetric planform

4.1.1 L/D Optimization

Performing *L/D* optimization at each flight speed, the *L/D* achieved by the optimized body shape and sweepback angle described in the following Table 1.

Table 1.Optimized values at each flight speed

M_∞	λ [deg]	*L/D*	*ML/D*
1.2	58.76	22.87	27.45
1.4	64.62	17.39	24.35
1.6	67.64	15.30	24.48
1.8	69.91	14.00	25.20
2.0	71.61	12.81	25.62
2.2	72.98	11.84	26.04

It turns out that taking a large sweepback angle λ may attain high *L/D* as flight speed increases. Although the *L/D* decreases with the increase in the flight speed, the *ML/D* will be optimized with about 24.4 to 27.5

An example of the body pressure distribution is shown here in Fig.5.

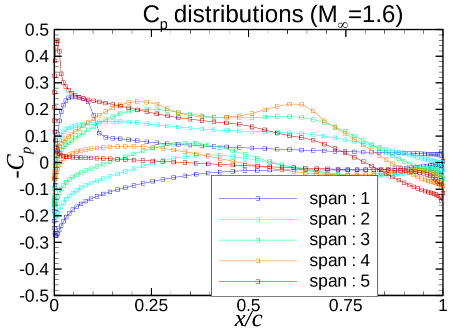

Fig.5. Pressure distributions on the wing (M_∞=1.6)

The shock wave does not arise on the body, and the distribution to which a lift becomes large especially in a middle-lower stream is mentioned as a feature. Although the value of the lift differs in other flight speeds, it becomes a similar pressure distribution. That is, it is possible to realize such a distribution in which the body shape and sweepback angle are optimized according to the flight speed.

4.1.2 Off-design performance

These shapes optimized at each flight speed can attain a high *L/D* also related to the flight speed, which originally was not optimized. If the *L/D* of the flight speed that is not an optimal point is examined in relation to the body shape optimized in M_∞=1.6 as an example, it will become like Fig.6. It is the value on the optimization body in each flight speed, which was set to "original" in the figure. Also excluding the optimal point (M_∞=1.6), a high *ML/D* is maintained and more than *ML/D* =23 can be attained in all domains at the flight speed calculated in this paper.

The OFW can achieve a high *L/D* also in different flight conditions even when the body shape is the same and can respond to the supersonic flight speed of a large range by changing the sweepback angle suitably according to the flight speed.

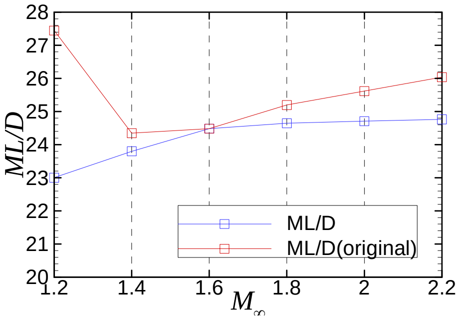

Fig.6. *ML/D* at the non-optimal flight speed using body shape optimized at M_∞=1.6

Furthermore, a high *L/D* can be further attained by giving incidence to the free stream in off-design conditions. *L/D* which can be attained when changing incidence α in the optimal point and some off-design conditions of the body shape optimized in M_∞=1.6 as shown previously, is summarized to Table 2.

Table 2.*L/D* and *ML/D* at some conditions using body shape optimized at M_∞=1.6

M_∞	α [deg]	*L/D*	*ML/D*
1.2	-2.0	20.20	24.23
1.6	0.0	15.30	24.48
2.0	2.0	12.36	24.71

It was shown that the optimization shape can achieve high *L/D* by giving incidence suitably also in off-design flight conditions.

4.1.3 Lift Distribution Optimization

The problem of stability is mentioned as one of the flaws of the OFW. How much of this problem can be solved is determined by the optimization of the body shape. Here, we consider that an ellipse distribution is ideal regarding the lift distribution of the span direction, and searches for the body shape, which realizes such distribution. This is concerned with the moment of the short axis. The objective function is arranged containing the deviation value from an ideal load distribution δ_{load}.

$$G = -\left(L/D\right)^n_{viscid} \times 1 / \left(1 + \sum_{span} \left|\delta_{load}\right|_{span}\right)^m \quad (3)$$

where m=n=1.

Optimizations are performed at each speed using this objective function as a simple *L/D* optimization. An example of the lift distribution obtained by these optimizations is shown in Fig.7. By the comparing calculation of the simple *L/D* optimization, it turns out that the lift distribution approaches to an ellipse distribution well all over the region of the span by the optimization of a lift distribution. On the other hand, in the flight of those other than the optimal point, it becomes a different distribution from an ellipse distribution.

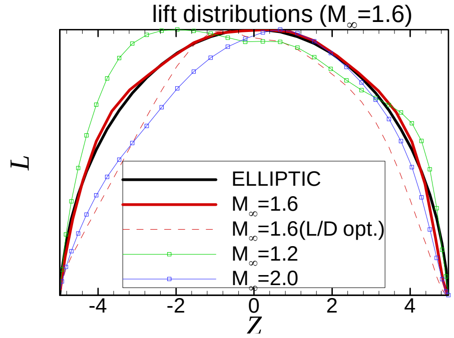

Fig.7. Lift distributions at each flight speed using body shape optimized at M_∞=1.6

The result of the optimization in all flight speeds is summarized in the following Table 3 regarding the sweepback angle, *L/D* and etc. Since the lift distribution was taken into consideration, *L/D* decreases twenty percent from the case of simple *L/D* optimization. High *L/D* still can be obtained. δ_{load} cannot be simply compared, when *L* differs, since it is the value standardized at the partial maximum of the lift in the span direction. In every flight speed, a lift distribution can be brought close enough to an ellipse distribution. However, in this optimization, a certain optimized shape cannot obtain the optimal δ_{load} under other flight conditions as already stated.

Table 3. Optimized values at each flight speed

M_∞	λ [deg]	L/D	ML/D	$\Sigma\lvert\delta_{load}\rvert$
1.2	57.73	20.16	24.19	1.101
1.4	63.11	16.51	23.12	0.997
1.6	67.02	14.58	23.33	0.884
1.8	68.14	12.20	21.96	1.088
2.0	69.72	10.84	21.68	0.846
2.2	72.14	11.47	25.23	0.89
1.6 (*L/D* opt.)	67.64	15.30	24.48	3.54

Since a lift distribution is unnaturally adjusted to the ideal distribution with a unique wings shape appearing so that it can grasp as in Fig.8, it is considered that an ideal lift distribution is unmaintainable on flight conditions other than the optimal point.

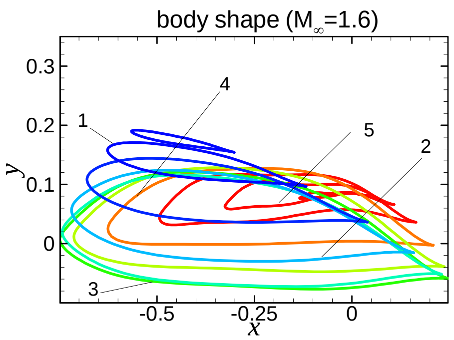

Fig.8. Body shape of lift distribution and *L/D* optimized at M_∞=1.6

4.2 Optimization with Symmetric planform

The OFW has been so far optimized using a model with the planform shown in Fig.2. This planform changes a little in both ends of the span, and it is made for the sweepback angle to become large locally. On the other hand, from here, it considers the planform to be in a simple ellipse shape, and allotting a body shape parameters symmetrically to a half-span position creates the OFW model of the symmetrical shape. It verifies what influence it has with the restricting shape symmetrically by performing the same optimization as the asymmetrical shape, and checking the performance on this symmetrical model of the OFW.

4.2.1 L/D Optimization

The result of the *L/D* optimization using a symmetrical shape body is shown in Fig.9 as compared with the result using an asymmetrical shape.

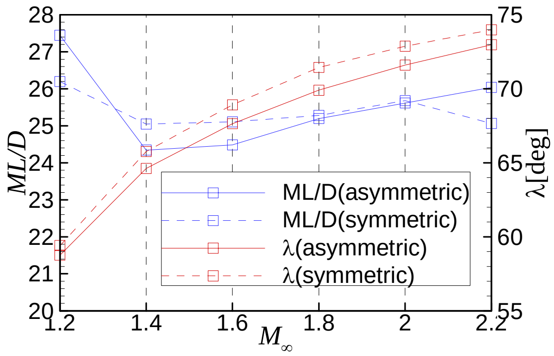

Fig.9. Optimized *L/D* and sweepback angle comparing symmetric and asymmetric shape

As shown in the figure, it is not clear which is more suitable between the symmetrical and asymmetrical shape in achieving *L/D*. On the other hand, with the symmetrical body, the sweepback angle becomes large about 1-2[deg] compared with the asymmetrical shape.

4.2.2 Lift Distribution Optimization

Using a symmetrical shape, the lift distribution of the span direction optimizations are performed, and a lift distribution of one example of these optimizations is shown below.

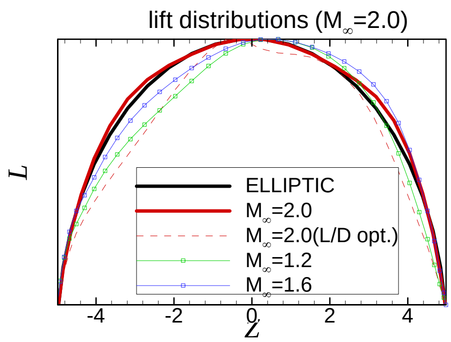

Fig.10. Lift distributions at each flight speed using symmetric body shape optimized at M_∞=2.0

In optimal flight speed, even if it compares with what was optimized only in regards to *L/D*, we can understand that lift distribution of the

OFW using a symmetric planform can fully approach ellipse distribution. Moreover, in off-design, the deviation from an ellipse distribution is suppressed as compared with the result (Fig.7.) in the asymmetrical shape. This optimization body shape is shown in Fig.11.

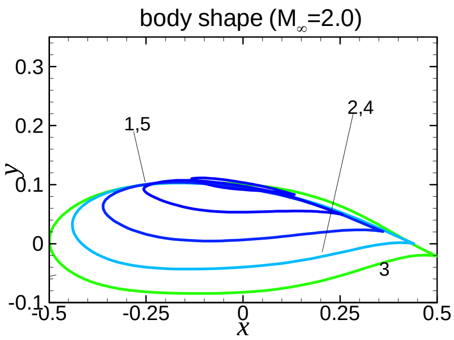

Fig.11. Symmetric body shape of lift distribution and *L/D* optimized at M_∞=2.0

There is no unique wing shape seen in the asymmetrical shape. It turns out that the body shape is not changing in particular, in order to change the lift distribution. Unlike the optimization using the asymmetrical shape, it is optimized by the natural body shape like simple *L/D* optimization. Each value under each flight condition of this symmetrical shape optimization body is summarized to Table 4.

Table 4. *L/D* and δ_{load} at each flight speed using body shape optimized at M_∞=2.0

M_∞	*L/D*	*ML/D*	$\Sigma\lvert\delta_{load}\rvert$
1.2	20.40	24.48	3.13
1.6	14.03	22.45	1.98
2.0	11.00	22.00	0.70

This body shape can attain *L/D* equivalent to the body shape acquired by simple *L/D* optimization. Furthermore, we can understand that this can also realize a lift distribution target.

Thus, the OFW can control a lift distribution, without reducing *L/D* greatly by defining a suitable body shape. In off-design, it shifts from the ideal a little. However, since the body pressure distribution changes with flight conditions continuously, it is possible to expect a lift distribution by changing from the optimal point. These facts lead to the expectation with the elements in connection with other stabilities that the OFW can be controlled only by the definition of the body shape.

As to the shape of the OFW, it is possible to prevent being optimized by optimizing using a symmetrical shape OFW model for an unnatural body shape. There is no fault, such as optimization *L/D* becomes low by using a symmetric shape. We can define the OFW body shape twice as accurately as the body of an asymmetrical shape by using a symmetric shape when assuming the same number of parameters. If these points are taken into consideration, it will be concluded finally that the symmetrical shape OFW model is more superior.

5 Conclusions

1. Downhill simplex method can be adapted for the optimization of OFW.
2. According to each flight condition of M_∞ =1.2～2.2, *L/D* optimization is possible for the OFW. Each optimized OFW can achieve *ML/D*=24.4 ～ 27.5. Moreover, each optimization body can achieve a high *L/D* also by changing the sweepback angle and incidence suitably in a different flight speed from the optimal point.
3. OFW can be optimized simultaneously with the *L/D* using an appropriate body shape for the lift distribution of the direction of span. But this ideal lift distribution may be realized by a local unique shape of the OFW in the asymmetrical planform. In this case, with off-design flight conditions, a lift distribution differs greatly from an ideal.
4. Optimization of *L/D* etc. is possible on a par with an asymmetrical-shaped OFW as well as in a symmetrical shape. Moreover, it is possible by assuming a symmetrical shape to prevent the optimization of an unnatural body shape. Furthermore, in terms of the definition of the body shape, a definition can be given twice as detailed as asymmetrical. Therefore, if these points are taken into consideration, it is appropriate to think that the body definition by a symmetrical shape is optimal for the OFW model.

References

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