Introduction to Waveriders

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Abstract

This paper explains first briefly what the waverider is and looks back its history. The discussion on their applications and design problems follows along with recent work. The paper emphasizes also the importance of CFD which has become one of the primary tools for the study of waveriders. Waveriders are basically considered being applied to high-speed vehicles. Three possible applications are discussed here. What is needed in those applications is exactly what waveriders can offer. As long as the interest in high-speed vehicles is alive, the waverider concept would never vanish. However, it is true that there is still a long way to go.

1 Introduction

1.1 *What are waveriders?*

A waverider is a hypersonic (or supersonic) vehicle which has an attached plane shock wave along its leading edge at design conditions. With the attached shock wave, the vehicle appears to be riding the top of the shock wave, thus termed ”waverider”. The purpose of keeping the shock wave attached to the leading edge is to capture the high-pressure gas behind the shock wave beneath the body, thereby increasing the lift. In contrast, with a detached shock wave, the high-pressure air leaks around the leading edge onto the top surface of the body. Because of this, the pressure on the bottom surface of the body is reduced, resulting in lift loss.

Figure 1. A waverider and a conventional vehicle [8].

The aerodynamic advantage of waveriders lies in the fact that their lift and L/D ratio are higher than conventional vehicles'. As can be seen in Figure 2, where the lift curves and the variation of L/D versus α are sketched, the waverider generates the same lift at a smaller angle of attack , thus achieving a higher L/D ratio (point 1aa) than that for the generic vehicle.

Figure 2. Lift and L/D versus angle of attack [8].

The method by which waveriders are designed is also a characteristic of waveriders. Waveriders are carved out from known flowfields generated not by a waverider itself but by other rather simple shapes such as a twodimensional wedge. For instance, the waverider first introduced by Nonweiler in 1959 is illustrated in Figure 3. The waverider, the so-called caret wing, is derived from the twodimensional flow past a wedge. The shape is determined by forming the solid surfaces from the streamlines of the flow. Various similar shapes can be formed since any streamlines can form the solid surfaces of a caret wing. Other basic shapes such as a cone can also be used to generate different types of waveriders. Nowadays conical-flow-derived waveriders have become the focus in all the waverider research , which provide a highly unform flowfield on the bottom surface, which in turn is perfect for scramjet integration.

Figure 3. A caret wing [1].

1.2 *The history*

The concept of the waverider was first introduced by Nonweiler in 1959. The waverider is the so-called caret wing described in 1.1. Expanding on its unique design method, new types of waveriders were introduced in Britain in 1969. These waveriders were the first derived from axisymmetric flows resulted from right-circular cones. In fact, over the years since 1959, the research has been carried out exclusively in Europe and the concept has received sporadic attention to the waverider concept. Those research in Europe are represented by the work by Townend [2]. In 1980, Raumussen, whose work was the main focus in the United States during the early 1980's, represented waveriders derived from flows over inclined circular and elliptic cones by using hypersonic small disturbance theory. A year later, he investigated also the effects of the curvature. The first attempt to search for optimized shapes had already been done by Cole and Zien in 1969. The shapes were derived from axisymmetric flows. Similar work was carried out later by Kim et al in 1980's. In those studies, they used the calculus and obtained the analytic expression for those shapes. However, including those optimization, all the earlier work had been carried out on the assumption that the flows were inviscid. Therefore, it was pointed out that because of the tendency that waveriders have large wetted surface areas, the skin-friction drag tended to greatly decrease the inviscid L/D ratio which looked promising. This made the waverider concept skeptical and wiped out an interest by researchers, in the United States in particular.

The possible next step was clearly to involve the effect of the skin-friction drag within the calculation or optimisation. It was first carried out by Bowcutt et al at the University of Maryland in mid-1980's [4]. The series of the waveriders were derived by using a numerical optimisation including viscous effects (also included boundary layer transition). The resulting family of waveriders, the so-called viscous optimized waveriders (VOW), yielded significantly high values of L/D. Incidentially, it is interesting to note that the optimisation revealed that a caret wing was an optimised shape for inviscid flows. The work at the University of Maryland went further and various types of waveriders were generated. For instance, it was found later that the waverider derived from flows over a power-law minimum drag body had a slightly higher L/D ratio [5]. Also, chemically reacting effects, viscous interaction effects, and the aerodynamic heating as a constraint function were included in the code [9].

During the early 1990's, the major part of the work being done at the University of Maryland, many have been carried out. Those work are mostly computational analyses in order to confirm the waveriders designed so far and to study off-design waveriders [11] [14] [16] [18] [20]. On the other hand, at the University of Maryland, the waverider optimisation code was used to generate a waverider for AGA maneuver . Also, by installing a 1-D scramjet code into the original code, optimum waveriders with a scramjet combustor were generated. On the other hand, Rasmussen designed unique shapes; waveriders with finlets, which have also high L/D ratio comparable to VOW's. At NASA Langley, the performance of VOW at high altitude, i.e. high Knudsen numbers, was estimated by using the direct simulation Monte Carlo method. Although it had been already pointed out for caret-wings [1] [2] , it was confirmed that the VOW yields a significantly low L/D ratio due to the drastically large skin-friction drag. Reviewing the recent progress, Tincher and Burnett conclude that a waverider flight test vehicle be the next logical step [19]. And a test flight of a scale model of a waverider by NASA Langley is coming up in November 1995.

2 Applications

2.1 *Hypersonic transportation (HST)*

The idea of hypersonic transportation is not very new. However, due to the insurmountable technical difficulties, it has been and is still quite difficult to put it into a practical step. Again, those difficulties involve all the areas; aerodynamics, propulsion and structure, and essentially cannot be treated separately, i.e. highly coupled, because of the necessity of the integrated system. This makes the design complicated.

However, there is a reason why one should not easily get rid of the concept of HST. The motivation is very nicely discussed in [1]. It is claimed in [1] that the ultimate goal of the aviation is to allow everyone to meet everyone else in the world immediately and cheaply, and the traveling time for comfortable journey is at most a few hours. The conclusion drawn from these claims is that we need an aircraft which can cover the global range ($\sim$ 20000Km) within a few hours; thus it has to fly at least M=4 $\sim$ 5. No existing aircrafts can do this ultimate job. We need to look for a new type of aircrafts. It leads us to waveriders which have larger L/D ratios than conventional hypersonic vehicles'. As can be seen in the Breguet equation, the range is proportional to L/D. Thus the generation of the waverider with high L/D ratio is the main focus on the aerodynamic design of HST. Also naturaly, the range is proportional to propulsive efficiency as well. Hence, the performance is the better the higher the efficiency. With these combined, L/D multiplied by propulsive efficiency can be treated as a single parameter to be enhanced.

There are also some other important factors in designing HST; the volume efficiency,the safety, etc. Besides, the low speed characteristics of waveriders is tempted to be improved further since it is of importance relevant to the problem of the noise at an airport.

2.2 *Aero-gravity-assisted vehicle (AGA)*

The planetary gravity assist has already become common for interplanetary flights. The technique is used to transfer gravitational energy of a planet to a spacecraft and accererate the spacecraft changing its direction too. The goal of this is obviously to reduce the flight duration significantly and to eliminate propulsion for orbit insertion. However, missions which require a very high velocity increment poses the problem that it is impossible to obtain such high dV only by gravity assist. Certainly it is possible by using massive planets such as Jupiter . However because of its remote location and a dangerous radiation, Jupiter is too far away for a certain mission and considered as one suited to gravity assist only. Thus, the new idea; aero-gravity assist, appears. It may be possible to gain a higher dV and a higher angular deflection as well by flying through the atmosphere of a palnet and taking advantage of a lift force in addition to gravity. Also, in this application, the importance of high L/D has been recognized. Lewis and Kathori derived closed-formed equations for aero-assisted hyperbolic trajectory as a function of L/D. It shows, for instance, that the maximum angular deflection of the trajectory through an atmosphere is proportional to its L/D and that high L/D serves to decrease the velocity decrement during transit through the atmosphere. An analysis insists that L/D as high as 10 would be necessary to acomplish a certain maneuver. Later, Anderson et al generated optimised waverider shapes for maneuvers through the Martian and Cytherean atmospheres by using the code developed at the University of Maryland. It was shown that as high L/D as almost 15 can be obtained for the case of flight through the atmosphere of venus, thus demonstrating the general validity of waveriders for this particular application.

2.3 *Reentry Vehicles*

The application of waveriders to reentry vehicles was proposed by Townend [2] and supported by theoretical and experimental work. The waverider shapes with sharp edges and recessed undersurfaces are exactly opposite to those with rounded leading edges and convex shapes such as space suttle orbitors which is commonly thought of as suitable for the purpose. However, the waverider shapes provide a higher reentry C_L, which allows an reduced flight velocity, thereby reducing aerodynamic heating rate. Additionally, it permits a reduction in wing area, thus in weight and skin-friction drag. And it is also expected that higher values of L/D improve the cross-range although L/D as high as that for hypersonic cruise vehicles would not be necessary.

In this application, low density and high temperature effects are more important than in HST due to the significantly higher flight velocities. Hence, it is inevitable to take into account such effects in the design. However, the difficulty of multiple interactions arises when such concave surfaces are put into a free molecular flows. Again, it has been found that waverider performance is deteriorated in rarefied flows. Much work would be necessary until it is applied in practice.

3 Aerodynamic design

3.1 *Aerodynamic design*

It is very difficult to deny the fact that CFD has dominated the field of gasdynamics. The advent of CFD has made it possible to solve problems that were extremely difficult to solve, in hypersonic regime in particular. Analytical methods such as HSDT have been and are still used by some researchers to design waveriders. However, with important phenomena for hypersonic flows such as chemically reacting effects which cannot be analyzed theoretically for flows except for very simple ones and has to be treated numerically, the use of CFD seems to be the proper way to go. The lack of facilities and those abilities also emphasizes the need of CFD.

However, CFD is not perfect in the sense that there are still some uncertainities in fluid dynamics that we must accept. First of all, there are no reliable methods for predicting transition from laminar to turbulent flow; when, where, and in what way transition occurs. This matter is of great importance in designing hypersonic waveriders since transition to turbulent flow causes significantly high skin-friction drag and aerodynamic heating. Secondly, once the flow become turbulent, it is also difficult to estimate accurately skin friction and heat transfer, particularly in three dimensional flows. On the use of CFD, we must rely on turbulence models. However, at least in the regions where strong interaction phenomena occur, there are no such models as to be used with a high level of confidence. Incidentially, the strong interaction is the primary reason why one needs to consider integrated systems. In addition, the prediction of flow separation has always been and is still a challenging problem in fluid dynamics. This problem is nothing but a viscous interaction. The power of CFD is throwing light on this problem.

Following the trend toward CFD, much works have been done in the past decade. Those work may be divided into two categories; design(or optimization) and analysis. The need of the latter comes from the former since the unique design method does not allow immediate analysis of the off-design conditions. The former may be represented by the work at the University of Maryland. Various waverider optimization codes have been developed, starting with the code including viscous effects for the first time. Also, a code which optimized waverider shape for scramjet integration was developed in 1992. And nowadays the work at University of Maryland has become the main stream of the research on waveriders in the United States. On the other hand, some analyses of off-design waveriders also have been carried out by using CFD. These simulations, in fact, confirm the aerodynamic advantage of waveriders at the design conditions and also the fact that L/D decreases at off-design conditions and by the rounding of the leading edges. An interesting analysis was done by Rault [14]. Aerodynamic characteristics of a VOW for high Knusen numbers was investigated by using the direct simulation Monte Carlo method. It was revealed that the VOW yields a significantly low L/D ratio due to the dramatically large skin-friction and that shocks are no longer attached to even sharp leading edges, thus no longer waveriders. The study shows the necessity of an optimisation code for waveriders in rarefied flows and the possibility that waveriders for high Knusen numbers might be very different from those for continuum flows. In such a way as to find an optimum shape and then analyze it, the design of waveriders appear to be inefficient. We could get a feeling of a promising waverider shape from an optimezed one. However, it would be difficult to keep its shape through the design phases wherein additional consideration such as engine integration or control systems would require the change in shape. In this sense, the optimisation is not global but local. Now that we have some optimised shapes in hand, what we really need is a code which can calculate the flow past a waverider, should be accurate, and which is sophisticated enough to take account of shockwaves in locations which are not known a priori, and possibly can treat a large number of parameters. Such a direct method would seem to be the most promising in the long run. However, it would be useful and powerful only when the computing time were reasonably short.

3.2 *Leading edge design*

The problem of the design of the leading edge involves the three areas mentioned earlier. And the preferences for each areas conflict one another. In terms of the thermal environment, blunt edges are preferable since a theory shows the heat flux at the stagnation point is inversely proportional to its nose radius and also blunt edges are expected to provide space to install thermal protection systems. On the contrary, sharp edges are attractive in terms of the aerodynamic efficiency since blunt edges may allow the formation of a dettached shock wave, which not only spoils the aerodynamic advantage of waveriders but also cannot fix separation lines at low speeds. Also the efficiency of propulsion is fairly sensitive to the design of the leading edge. In this respect, sharp edges are preferable since blunt edges, in turn the formation of bow shock, yield the thicker boundary layer and the greater loss of the total pressure of the flow, thereby degrading the propulsive efficiency. Therefore, the design of a waverider leading edge involves a tradeoff between making the leading edge sharp enough to get acceptable aerodynamic and propulsion efficiency, yet blunt enough to use a reliable thermal structure system. A study in this context has recently been carried out by Blosser et al. In this study, wing leading edge concepts were considered for a particular Mach 5 waverider and the analysis for a promising concept was done in detail. It was shown that the use of highly conductive materials, which was first proposed by Nonmeiler in 1952, was more practical rather than other concepts such as ablation or active cooling. In addition, the detailed numerical analysis yields the promising results for the concept. For instance , temperature were found to be within the acceptable limits of the material used. Following this study, experimantal demonstration is necessary to confirm the results.

4 Concluding Remarks

It is clear that waveriders are absolutely potential candidates for the application of the hypersonic flights since they offer better performance than other conventional vehicles do. However, there is still much more to be done in hypersonics itself, such as experimental investigations into transition processes, for example. Those are closely related to the progress of waverider research. With those things in mind, a sophisticated design method should be developed, which can estimate the performance of waveriders in various conditions. And the design of waveriders would have to rely greatly on CFD, which explicitely means the progress of the computer technology and fluid dynamics. Also, it is very likely that waverider shapes could be very different depending on design methodologies as well as applications toward which they are designed. It is true that some (or many) are skeptical particularly about HST. However, it is also true that that is why someone has to show it to be feasible and makes it welcomed.

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