A Morphing Structure for an Adaptive Wind Tunnel Nozzle

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Abstract

The inlet to a hypersonic air-breathing engine is in a complicated aerodynamic environment. The ability to change the shape of the inlet offers the opportunity to control a variety of flow phenomena. Morphing structures based upon cellular-core sandwich panels provide a platform for changing the shape of the aerodynamic surface without introducing seals and gaps. As a demonstration of these concepts in an aerodynamic setting, a morphing nozzle for a supersonic wind tunnel has been designed and constructed. This paper will describe the techniques used to design the nozzle for shape changes in the range of Mach 3 to Mach 4.

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1 Introduction

The performance of air-breathing hypersonic engines - ramjets and scramjets - is very sensitive to the aerodynamics at the engine inlet. A complicated shock structure forms on the vehicle forebody and inlet cowl which is used to slow and compress the incoming air, but which can also be transformed into a deleterious Mach stem configuration, choking the inlet (see, for example, Sudani and Hornung (1998)). During acceleration or deceleration and while maneuvering, the engine is forced to perform off the design Mach number and the inlet will not function at its maximum efficiency. Boundary layer separation can result in loss of pressure at the inlet opening. These problems can be reduced or eliminated by employing a shape-adaptive inlet. However, current concepts for shape changing involve complex joints, seals and gaps which are difficult to build and have deleterious aerodynamic consequences.

Continuous surface shape morphing concepts based upon sandwich structures with actuated core members were proposed by Hutchinson et al. (2003) and demonstrated by dos Santos e Lucato et al. (2004). Such structures are based upon cellular core sandwiches, which are described in detail in Evans et al. (1998), Evans (2001) and Evans et al. (2001). A morphing wind tunnel nozzle is a demonstration of these types of morphing structures in supersonic aerodynamic applications. The ability of the morphing surface to conform to an aerodynamic shape which is sensitive to small non-uniformities will be shown. Moreover, the morphing nozzle is a a ramjet inlet operating in reverse: that is, the nozzle produces an isentropic acceleration from subsonic to supersonic velocity, while the ramjet inlet decelerates air from supersonic to subsonic velocity.

This paper is organized as follows: First, the existing wind tunnel installation and the nozzle to be replaced are described. Second, the computational fluids modeling necessary to predict the aerodynamic behavior of the morphed inlet will be briefly described. Third, a systematic method for designing morphing inlets and controlling the actuators will be proposed. Finally, some limitations to these techniques will be discussed.

2 The current nozzle

The existing fixed nozzle, which is to be replaced by a morphing nozzle, is installed in a supersonic in-draft wind tunnel at the Princeton University Department of Mechanical and Aerospace Engineering. The tunnel draws...
ambient air from the lab through the nozzle, which gives constant and easily measurable stagnation conditions of room temperature and atmospheric pressure. The diverging end of the nozzle is attached to a diffuser via a flange, with the converging end of the nozzle open to the room. The diffuser connects the nozzle to an air ejector system, which maintains the low back pressure that pulls in air from the room and creates supersonic flow through the test section. The wind tunnel is designed for Mach 3 flow, but it is capable of producing flow speeds from Mach 2 to Mach 4 at relatively low Reynolds numbers.

At Mach 3, the test section pressure is 20 Torr and the ejector back pressure is 150 Torr. A custom designed diffuser achieves the necessary pressure recovery after the test section. The diffuser slows the flow in a series of oblique shocks, decreasing the loss of total pressure produced by a normal shock diffuser. Quartz windows are installed in the test section of the nozzle to allow for high-quality Schlieren imaging to determine flow quality, and pressure taps are placed at several points along the length of the nozzle to determine flow speeds. The current nozzle is 450 mm long and 50 mm wide, and is depicted in Figure 1. It will be replaced by a morphing nozzle of equal size to minimize the tunnel modifications necessary.

Figure 1: A photograph of the existing wind tunnel inlet. Quiescent lab air is drawn into the right end of the inlet and accelerated to supersonic velocity by an ejector system.
3 Computational fluids modeling

Computational fluid dynamics (CFD) was used to determine the ideal nozzle shapes for the adaptive tunnel. A viscous code was designed to optimize the nozzle shape to produce a shock-free, isentropic flow based on a given inlet pressure distribution. The adjoint optimization methods used to calculate the optimal shapes are described in Jameson (1988) and Jameson (1990). The nozzle curves were designed with a fixed exit diameter, allowing the throat area to vary between Mach numbers. The total length of the nozzle was also fixed. Both fixed dimensions were constrained by the current wind tunnel configuration. The reduction in effective exit area due to boundary layer effects was accounted for in these curves by a slight enlargement of the exit area, deviating from the inviscid, isentropic throat-to-exit ratio for each Mach number. For the purposes of the current design, nozzle curves were computed for Mach 3 and Mach 3.8 flow speeds; these shapes are presented in Figure 2.

![Figure 2: The two desired shapes for the morphing wind tunnel nozzle. The nozzle is manufactured to conform to the Mach 3 shape, and must be morphed to attain the Mach 3.8 shape. The anti-streamwise distance is the length from the connection between the diffuser and the nozzle in the direction opposite the flow.](image.png)
4 Designing a morphing nozzle

An actuated structure which is a variant of a corrugated sandwich beam is shown in Figure 3. The vertical and oblique members provide actuation and shear stiffness, respectively, and are pin-connected such that they transmit only axial forces. The passive aerodynamic surface is a continuous curved beam of streamwise length $\ell$, connected to actuated members at $N$ unequally spaced nodes.

![Figure 3: Isometric drawing of a morphing sandwich structure with actuators.](image)

The required shape changes and slopes are small; it is assumed that the deflections from individual actuators can be summed linearly, and that the deflection from a single actuator can be calculated starting from a flat plate. The morphing nozzle is constructed so that it has the appropriate curvature for an isentropic expansion to Mach 3 when it is unactuated. As a consequence, the required shape change is the difference between the initial Mach 3 shape and the shape for the intended Mach number. This difference is $\phi(x)$, where $x$ is the longitudinal coordinate along the length of the surface, and $x = 0$ is the location of the connection of the nozzle to the diffuser. This contour will be approximated by $\omega$, which belongs to the family of curves which can be obtained by deflections of the actuators in the morphing structure. An adequate approximation is found in the least-squares sense, which means that the function $\psi$,

$$\psi = \int_0^{l} (\phi - \omega)^2 \, dx,$$

is a minimum. The function $\omega$ is conveniently expressed by $\omega = a_i \omega_i$, where the $\omega_i$ are the linearly independent, and linearly summable, functions.
produced by displacements of the individual actuators. The Rayleigh-Ritz method is then used to determine the constant coefficients $a_i$ by simultaneously solving the equations:

$$\frac{\partial \psi_i}{\partial a_i} = \int_0^l 2 [\phi - a_j \omega_j] \omega_i dx = 0. \quad (2)$$

This is achieved through the solution of the linear system $b_{ij} a_j = r_i$, where

$$b_{ij} = \int_0^l \omega_i \omega_j dx, \quad (3)$$

and

$$r_i = \int_0^l \phi \omega_i dx. \quad (4)$$

The solution vector $a_i$ gives the mix of the functions $\omega_i$ required to approximate most closely the desired surface profile $\phi$, and hence provides the displacements of the set of actuators. This procedure assumes that the passive surface remains elastic, and that the oblique members are rigid. Small deflections are also assumed, such that the deflections of individual actuators can be superposed, and such that the longitudinal change in position of the nodes can be neglected.

The approximation can be improved by varying the locations of the nodes. If the nodal locations are given by $x_{N_i}$, then the gradient of the cost function $\frac{\partial \phi_i}{\partial x_{N_i}}$ is calculated numerically given the present location of the nodes. The nodes are then adjusted using a path of steepest descent, the cost function is recalculated and the process is iterated. While this is guaranteed to improve the solution and eventually find a local minimum, finding the global minimum is not assured.

The morphing nozzle must change from a Mach 3 geometry to a Mach 3.8 geometry. The two required shapes are shown in Figure 2. Because the nozzle is constructed to conform to the Mach 3 shape, the actual morphing needs only produce the deflections equivalent to the difference between the Mach 3 shape and the Mach 3.8 shape. This difference is shown in Figure 4.

The shape functions, $\omega_i$, are determined by the configuration of the morphing structure and the location of the nodes connecting the actuators to the aerodynamic surface. For the structure displayed in Figure 3, the functions $\omega_i$ are linear sums of the deflected shapes of cantilever beams fixed at the leftmost end and subjected to a unit displacement at each actuator location. A typical shape function is shown in Figure 5 for the third of seven actuators, and a full set of shape functions is shown in Figure 6.
Figure 4: The net difference between the existing Mach 3 shape and the desired Mach 3.8 shape.

Figure 5: A typical shape function for a morphing aerodynamic surface. In this example, the third of seven actuators has been displaced.
Utilizing the optimization procedure described above, this set of shape functions is modified and the quality of the shape change is improved, resulting in the fit shown in Figure 7. The difference between the desired shape and the best shape attainable with this morphing structure is presented in Figure 8.

The results of the optimization algorithm are combined with the pressure distribution calculated by CFD to choose actuators which can sustain the predicted loads on the structure. Because this is an in-draft wind tunnel, the maximum pressure difference across the morphing surface is one atmosphere. The actuation is provided by seven electric stepper motors, each with a resolution of 5 \( \mu \text{m} \), which are independently controlled by a LabView system.

5 Concluding comments

The morphing surface will deviate from the desired shape for two reasons: because it is inherently an approximation to the desired shape and because control of the surface is not perfect. Controlling the morphing system to conform to the desired shape is dependent upon several factors:

i. resolution of the actuators;

Figure 6: A typical set of shape functions for a morphing aerodynamic surface with seven actuators.
Figure 7: The quality of the theoretical fit after the shape functions are improved.

Figure 8: The difference between the desired shape and the optimal shape found by the shape fitting algorithm.

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ii. manufacturing tolerances of both the surface shape and the actuation substructure;

iii. temperature changes and pressure loads which cause geometric changes in the surface;

iv. accurate predictions of the attainable shape given the chosen actuation system.

Each of these may result in the aerodynamic surface not conforming to the ideal approximated form that is predicted by the shape-fitting algorithm. The aerodynamic consequences of these imperfections must be assessed experimentally and computationally. It is anticipated that better approximations will be attainable by using an algorithm with a more sophisticated optimization criterion than a simple least squares fit. For example, it is believed that the calculation of the quality of the fit should be weighted to give greater importance to the fit near the nozzle throat than near the connection with the diffuser.

The morphing structure, when manufactured, will be installed in the Princeton wind tunnel system and tested under conditions ranging from Mach 2.4 to Mach 3.8. Pressure taps and Schlieren imaging will be used to assess the quality of the flow field and to compare the actual flow field to the flow predicted by CFD. When the performance of the morphing tunnel has been completely characterized, it will be used for experiments which involve Mach number changes, such as acceleration and deceleration or Mach stem formation.

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