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Analysis of a Device for Generating Perturbations in Supersonic Wind Tunnels

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The analytical study of a device called the dual plate disturbance generator is described. This device has been proposed as a mechanism for generating gustlike perturbations in supersonic wind tunnels. The device is envisioned as a means to experimentally validate dynamic models and control systems designed for high-speed inlets. The dual plate disturbance generator is composed of two flat trapezoidal plates that modify the properties of the flow ingested by a supersonic inlet. One plate may be oscillated to generate small perturbations in the flow. The other plate is held stationary to maintain a constant angle of attack. Four modes of operation exist; each mode is distinguished by the relative position of the plates and the structure of the resulting flowfield. Design equations and performance maps were developed for one of the four modes of operation using an idealized approach and the compressible flow relations. The maps and equations were then used to design and evaluate a disturbance generator for a 3.05 × 3.05 m (10 × 10 ft) supersonic wind tunnel. Results suggest that, under certain conditions, the proposed device can meet and exceed established gust generator requirements. However, further study is required to identify the optimal mode of operation and establish feasibility.

Nomenclature

A	=	amplitude
D	=	inlet diameter
dm	=	differential element of mass
f	=	frequency, Hz
H	=	angular momentum
$\dot{H}$	=	torque
h	=	height of uniform flowfield
I	=	mass moment of inertia
L	=	length parameter
M	=	Mach number
t	=	time
W	=	plate width
x	=	longitudinal coordinate, measured in the direction of the flow
y	=	horizontal coordinate, measured perpendicular to the direction of the flow
z	=	vertical coordinate, measured perpendicular to the direction of the flow
α	=	angle of attack
β	=	yaw angle
δ_{i-j}	=	turning angle, flow deflection, or change in flow angle between regions i and j
δM	=	Mach number perturbation, $\delta M = M(t) - M(0)$
δP_T	=	total pressure perturbation, $\delta P_T = [P_T(t) - P_T(0)]/P_T(0)$
Θ	=	angular position
$\dot{\Theta}$	=	angular velocity
$\ddot{\Theta}$	=	angular acceleration
θ_i	=	angle of the flow in region i relative to a fixed horizontal reference frame
σ_{i-j}	=	angle of the shock between regions i and j measured relative to the flow in region i
ω	=	frequency, rad/s

Subscripts

cm	=	center of mass
gp	=	gust plate parameter
hinge	=	hinge point where two plates touch
inlet	=	plane where flow first impinges on inlet centerbody
max	=	maximum parameter value
min	=	minimum parameter value
nom	=	nominal parameter value
yy	=	generic axis for moment of inertia

Introduction

IN recent years, the international aerospace community has shown renewed interest in the development of a new generation of supersonic transport aircraft. The propulsion systems being developed for these aircraft are typified by a low-bypass, subsonic turbofan connected to a mixed-compression inlet as shown in Fig. 1. Flow enters the inlet at supersonic speeds where it is reduced to subsonic velocities by a normal shock before entering the engine. To ensure safe, efficient operation, the normal shock must remain inside the inlet despite unexpected atmospheric perturbations. Expulsion of the normal shock, a phenomenon known as unstart, can have catastrophic consequences during flight. An inlet control system is required to avoid and/or minimize the impact of the unstart phenomenon on aircraft operation.

To design a controller properly for the inlet, some knowledge of the flow dynamics is required. Preliminary knowledge is often obtained from time-accurate simulations, which are then used for initial validation of the control laws. Final validation of the control is accomplished experimentally. Proper experimental results will produce data that characterize the inlet dynamics with (closed loop) and without (open loop) the control. Data from open-loop tests are also useful for validating simulations that may then be used to refine control strategies. Closed-loop tests provide a mechanism for tuning and validating the control against actual hardware.

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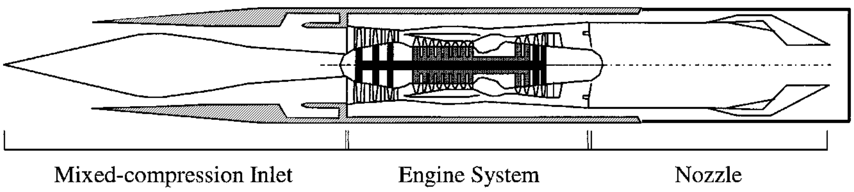

Fig. 1 Typical high-speed inlet-engine configuration.

The data required for dynamic validation usually take one of two forms, based on the form of the excitation. If the excitation is a step disturbance, the time responses of measured variables, typically static pressures, are used to evaluate the analytical models. If the excitation is a sine wave with continuously varying frequency, then the time response data are analyzed using spectral methods to obtain the system response in the frequency domain. To obtain useful data in either case, it is important for the highest excitation frequency to meet or exceed the corner frequency (bandwidth) of the propulsion system.

Historically, experimental data describing the inlet dynamics have been obtained by exciting the freestream flow upstream of the inlet, or by exciting the internal subsonic flowfield. A number of devices have been successfully used to perturb the internal subsonic flow. These devices have produced frequency response data with bandwidths as high as 2200 rad/s (350 Hz) in test rigs[1] and 1260 rad/s (200 Hz) in subscale inlets.[2] The devices used to perturb subsonic flow cannot be used to perturb the supersonic flow ingested by the inlet. Attempts to obtain the frequency response of high-speed inlets to high-frequency changes in freestream supersonic flow have been largely unsuccessful. The problems and difficulties that arise are best illustrated by a review of the reports documenting those attempts.

In 1951, Fox[3] produced continuously varying inlet Mach numbers in a constant Mach number tunnel by using oblique shocks originating from the leading edge of a flat, trapezoidal plate mounted below and forward of an inlet. By changing the angle of the inlet/plate assembly, he was able to change the strength of the shock wave and, consequently, the inlet Mach number. Although the results reported by Fox were strictly steady state, they provided a foundation for future dynamics and control studies.

Hurrell et al.[4] evaluated the response of a ramjet with a closed-loop control to changes in the upstream Mach number using Fox's[3] approach. They carried the approach one step further when they measured the transient response of the ramjet while changing the angle of the inlet/plate assembly relative to the flow. Unfortunately, the slow-moving assembly was "not fast enough to impose noticeable errors from the set point during the transients."[4] The change in inlet total pressure during the disturbance is not documented. From the Hurrell et al.[4] results, it can be shown that less than $1\frac{1}{2}$ deg of turning will produce the reported change in Mach number (from 1.84 to 1.79 in 0.6 s) with a negligible change in the total pressure.

Wasserbauer and Whipple[2] also used a flat, trapezoidal plate to generate changes in the flow upstream of the inlet. However, they mounted and actuated the inlet and the gust plate independently. By oscillating the gust plate $\pm\frac{1}{2}$ deg about the horizontal, they were able to generate sinusoidal freestream disturbances at 75 rad/s (12 Hz). At a tunnel Mach number of 3.0, this oscillation produced a 0.05 change in inlet Mach number, a 1-deg change in inlet angle of attack, and a negligible change in inlet total pressure.

Sanders et al.[5] tried a different method of perturbing the freestream supersonic flow. They placed a rectangular, flat plate in the tunnel throat and rotated it from a vertical to horizontal position in 15 ms. This device produced a decrease in Mach number from 2.57 to 2.42, a change in local airflow angle from −3.9 to −1.0 deg, and an increase in total pressure recovery from 0.955 to 0.991. The bandwidth (corner frequency) of this device was only about 8 Hz.

Cole and Hingst[6] reported the results of an analytical study in which they investigated four devices for potential use as gust generators. The four devices were a triangular airfoil, tunnel throat modulation (e.g., flex wall or collapsible centerbody), a flat plate, and the blast wave from a shock tube. They concluded that, to simulate atmospheric-like disturbances, the gust generator should produce relatively uniform perturbations in the flowfield with little or no change in angle of attack. Furthermore, the disturbance should be composed of a decrease in Mach number of at least 0.05 Mach and a change in total pressure of at least 8%. Cole and Hingst found that the devices included in this study could not meet their gust generator requirements.

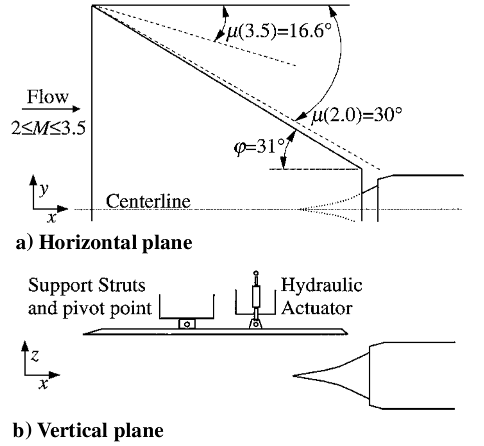

Fig. 2 NASA John H. Glenn Research Center at Lewis Field gust plate.

Of the devices just discussed, the gust plate used by Wasserbauer and Whipple[2] produces the most uniform flowfield. Because it provides a basis for the new gust generator design, a slightly expanded review of the device is in order.

Gust Plate

The device currently used as a gust generator at the NASA John H. Glenn Research Center at Lewis Field is the gust plate first used by Wasserbauer and Whipple.[2] Although this device does not meet the requirements defined by Cole and Hingst,[6] it has been used to obtain a limited amount of data for validation of computer simulations and control methodologies.

In the horizontal plane, shown in Fig. 2a, the gust plate has a trapezoidal shape that keeps Mach waves generated by the leading-edge corners from interfering with the flow under the plate. The 31-deg sweep angle is 1 deg larger than the Mach angle resulting from a 2.0 freestream Mach number, the lowest Mach number at which the tunnel operates.

In the vertical plane, shown in Fig. 2b, the pivots for the support struts have been placed at an axial coordinate approximately corresponding to the center of mass. By locating the hinges close to the center of mass, inertial effects of the mass are minimized and the frequency response is maximized.

As a disturbance generator, the gust plate has three main deficiencies. First, it produces unacceptable changes in inlet angle of attack. Second, it does not produce total pressure perturbations with acceptable amplitude. Third, it has insufficient frequency bandwidth due primarily to its large size and weight.

Summary of Gust Generator Requirements

The requirements used to assess the acceptability of the new gust generator are based both on the capabilities of the original gust plate and the gust criteria of Cole and Hingst.[6] The combined requirements, listed in Table 1 and detailed by Melcher,[7] are briefly described as follows.

Table 1 Summary of requirements for proposed gust generator

Requirement	Description
$D_{\text{inlet}} \leq 50.8$	Maximum inlet diameter, cm
$W_{\max} \leq 274.3$	Maximum plate width, cm
$\delta M_{\text{inlet}} \geq 0.05$	Amplitude for Mach perturbation at 0.1 Hz
$\delta P_{T,\text{inlet}} \geq 0.08$	Amplitude for total pressure perturbation at 0.1 Hz
$f_{\max} \geq 70$	Frequency bandwidth, Hz
$-0.1 \leq \alpha \leq 0.1$	Change in angle of attack, deg
$2.1 \leq M_1 \leq 2.4$	Mach range for the inlet

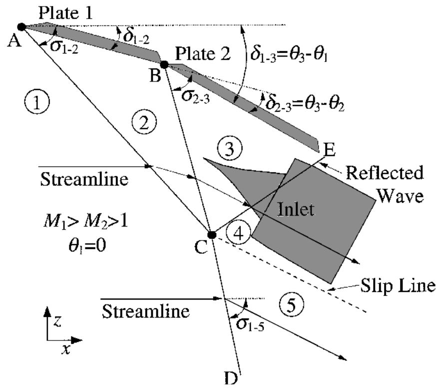

Fig. 3 Flowfield diagram for the dual plate disturbance generator (vertical plane).

The requirements for maximum inlet diameter and maximum plate width ensure that the new device will meet the same geometry constraints as the original gust plate. The first requirement guarantees that the new device will support tests of small-scale inlets up to 51 cm (20 in.) in diameter. The second requirement ensures that the new device will fit in the wind tunnel without developing wall boundary-layer interactions. The next three requirements, beginning with the Mach perturbation, are obtained directly from Cole and Hingst.[6] Realistically, the frequency bandwidth requirement is a function of inlet size; smaller inlets will have higher bandwidth requirements. Thus, the device will be more useful if the bandwidth greatly exceeds this requirement. The constraint on changes in angle of attack is designed to allow for some flexibility in the gust generator design. High-speed inlets are normally designed to accommodate a change in angle of attack of at least 1 deg. The final requirement is based on a desire to maximize the frequency response of the proposed device. Minimizing the Mach range of interest will increase the frequency bandwidth by decreasing the size of the plate.

Description of the Dual Plate Disturbance Generator

The rest of this paper describes a new device proposed for use as a gust generator. The dual plate disturbance generator is composed of two flat trapezoidal plates. The device may be operated in one of four modes. These modes are distinguished by the relative position of the plates and the resulting flowfield. The analysis presented in this paper addresses only the mode where each plate turns the flow, causing it to be compressed. For this mode, the orientation of the plates in the vertical plane is shown in Fig. 3. Two plates, connected by a flexible joint or hinge, modify the flow ingested by the inlet. Plate 1 is designed to meet perturbation requirements. It will rotate about the hinge line, creating perturbations in the flow. Plate 2 is designed to meet requirements for constant angle of attack. In this simplified analysis, a region of uniform flow will exist under each plate with direction parallel to the plate. Therefore, holding both the inlet and plate 2 stationary will result in a constant angle of attack regardless of perturbations in the flow caused by plate 1. Further analysis will determine whether the device is able to meet the other requirements.

Compressible Flow Analysis in the Horizontal Plane

The bulk of the analysis for the proposed disturbance device has been devoted to the rather complex flowfield in the vertical plane. However, an understanding of the flow in the horizontal plane is also required to minimize the overall size of the plate.

The plates require a trapezoidal shape in the horizontal plane based on the Mach wave considerations used to design the original gust plate. The lower bound on the sweep angle for each plate may be calculated from the Mach angle as follows:

$$\varphi > \mu = \sin^{-1}(1/M), \qquad M \geq 1 \tag{1}$$

From the inverse relationship between Mach number and sweep angle, it is obvious that low Mach numbers will tend to decrease the disturbance bandwidth by increasing the plate width and, consequently, the size and mass. This will be an important consideration in subsequent attempts to maximize the bandwidth of the proposed gust generator.

Compressible Flow Analysis in the Vertical Plane

The character of the flowfield for the proposed gust generator is analogous to the general case where supersonic flow is compressed through more than one angle, generating a family of oblique shocks that coalesce. A description of the flowfield for such a system is given by Anderson.[8] In Fig. 3, this approach is applied to the proposed disturbance generator.

A weak oblique shock AC is formed when the supersonic flow in region 1 encounters plate 1 with initial deflection δ_{1-2} and is turned. The deflection sets the flow angle in region 2 parallel to the plate. A second oblique shock BC is formed when the flow in region 2 encounters plate 2 with deflection δ_{2-3}. This deflection sets the flow angle in region 3, which is also parallel to the plate. Because the second shock has a lower upstream Mach number than the first shock, it has a steeper angle and eventually the two shocks coalesce into CD. Now, the properties in region 3 have gone through two shocks, but the properties in region 5 have gone through only one shock. Therefore, the entropy in regions 3 and 5 must be different, and a slip line, originating at the point of intersection, will exist downstream of the shock structure. Furthermore, for the slip line to exist, the static pressure and the flow angle in regions 4 and 5 must be equal. However, it is generally impossible to find a single shock that will result in the same pressure and flow angle as the two intermediate shocks. Anderson[8] notes that nature resolves this problem by inserting a reflected wave CE that originates from the intersection of oblique shocks AC and BC. This wave will take a form that appropriately resolves the flow. For the work reported here, the wave is an expansion that effects the flowfield in regions 4 and 5 by turning it slightly away from the plate. Should the wave intersect plate 2, a reflected wave will form at the point of intersection to turn the flow back parallel to the plate.

Note the placement of an inlet in the flowfield. The inlet should not be placed in region 2 because it is the same as operating the inlet with a single plate. A single plate cannot meet the established requirements. It would also be unacceptable for the inlet to span regions 4 and 5. Here, the flow properties are uniform only when the two plate angles are the same, that is, $\theta_2 = \theta_3$. If a slip line exists, the static pressure and flow angle in the two regions will be equivalent, however, the Mach number and temperature will not. Finally, the inlet should not be placed solely in region 5 because perturbations in the angle of plate 1 produce negligible changes in the flow properties. This leaves regions 3 and 4 as the logical place to locate an inlet.

It is evident from Fig. 3 that the structure of the flowfield is not only a function of the freestream Mach number and the plate angles, but the plate lengths as well. Length parameters are defined in Fig. 4. L_1 and L_2 represent the respective lengths of plates 1 and 2. h is a distance measured perpendicular to plate 2 from the bottom of the plate to the intersection of the two shocks. L_{2a} is the distance from point B, the leading edge of plate 2, to point F, the point at which the perpendicular through C intersects the bottom of the plate.

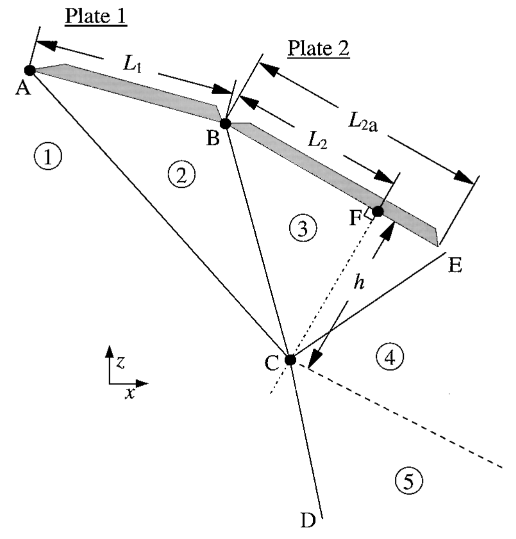

Fig. 4 Length parameters for the dual plate disturbance generator (vertical plane).

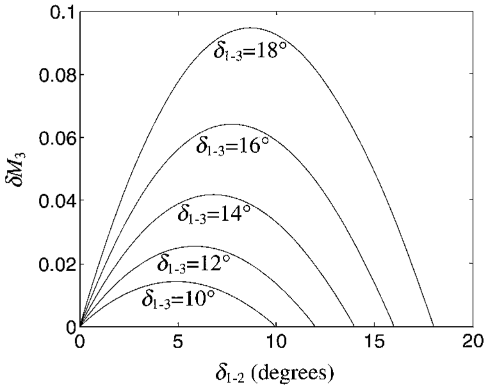

Fig. 5 Variations in region 3 Mach perturbation as a function of the initial and total flow deflection.

This distance, L_{2a}, is the minimum length that results in a uniform flowfield of height, h.

Consider an inlet placed in region 3 or 4 with axis parallel to plate 2. The inlet diameter will be bounded by the distance between plate 2 and the slip line when measured perpendicular to the plate CF. The location of point C, and hence the slip line, is dependent on four parameters: the freestream Mach number M_1, the two turning angles δ_{1-2} and δ_{2-3}, and the length of plate 1 L_1. The Mach number and the turning angles will determine the angle of the oblique shocks and, hence, the angles of triangle ABC. It is then a matter of simple geometry to show that h and L_1 are directly proportional. This means that the size, mass, and frequency bandwidth of the disturbance generator are all proportional to the largest inlet diameter of interest.

Results from Solution of the Compressible Flow Equations

A set of equations describing the idealized flowfield of the proposed gust generator is given by Melcher.[7] In this section, maps resulting from the solution of these steady-state isentropic flow and oblique shock equations are discussed. The maps, Figs. 5–9, show how properties of the flow vary as a function of freestream Mach number and plate angle.

The flow property maps were developed by first selecting a nominal inlet Mach number and a nominal angle for plate 1. $M_{3,\mathrm{nom}} = 2.35$ was selected as a typical inlet Mach number for supersonic transports. A horizontal orientation, $\theta_{2,\mathrm{nom}} = \delta_{1-2,\mathrm{nom}} = 0$, was chosen for plate 1 because it simplifies the maps.

After choosing values for $M_{3,\mathrm{nom}}$ and $\delta_{1-2,\mathrm{nom}}$, several nominal values for the angle of plate 2 were chosen such that $\theta_{3,\mathrm{nom}} = \delta_{1-3,\mathrm{nom}} = 10$, 12, 14, 16, and 18 deg. Given the nominal angle

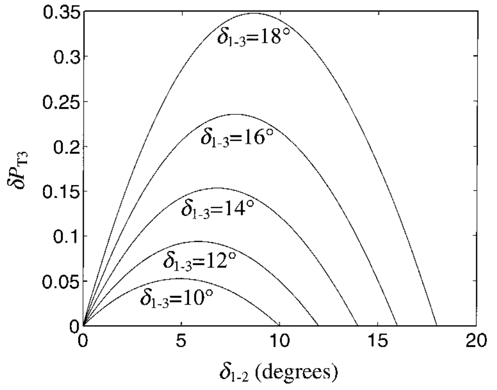

Fig. 6 Variations in region 3 total pressure perturbation as a function of the initial and total flow deflection.

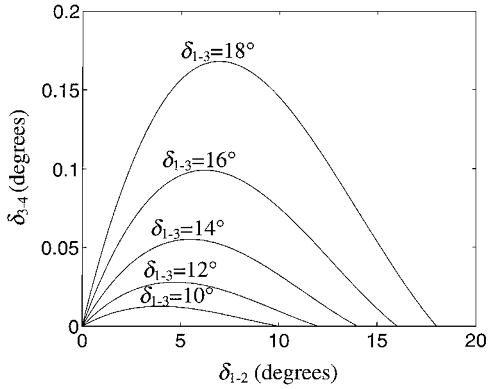

Fig. 7 Variations in the change in flow angle between regions 3 and 4 as a function of the initial and total flow deflection.

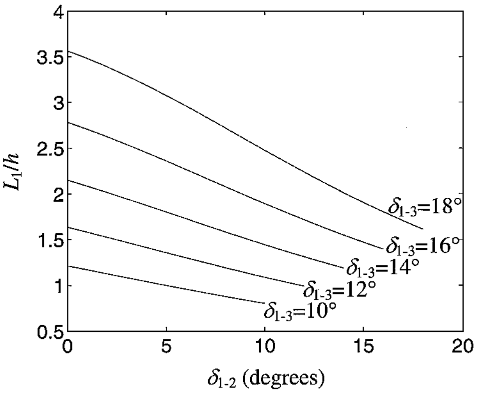

Fig. 8 Variations in the length of plate 1 as a function of the initial and total flow deflection.

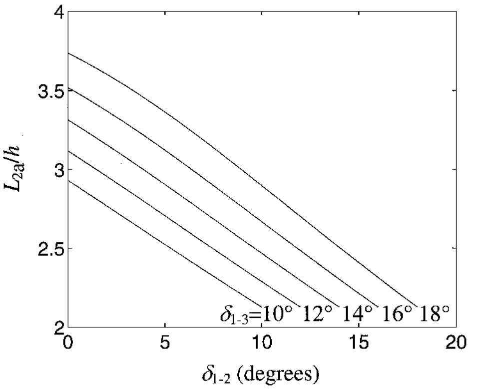

Fig. 9 Variations in the length of plate 2 as a function of the initial and total flow deflection.

of plate 1, each value of δ_{1-3} requires a unique freestream Mach number to match the nominal inlet Mach number of 2.35, that is, $M_{1,\mathrm{nom}} = 2.812$, 2.929, 3.060, 3.209, and 3.384, respectively. With the freestream Mach number and the angle of plate 2 held constant, the flowfield properties may be calculated as plate 1 is varied from 0 deg to θ_3.

In Fig. 5, the Mach perturbation for region 3 is shown as a function of δ_{1-2} and δ_{1-3}. Two observations can be made from this result. First, it appears that values of δ_{1-3} larger than 15 deg will be needed to meet amplitude requirements of 0.05 Mach. Note that blockage and geometry considerations may make it impossible to operate the wind tunnel with the hardware positioned at these relatively large angles. In addition, although higher values of δ_{1-3} allow for larger perturbations in the flow, they require a higher freestream Mach number. In general, the wind tunnel should be operated at the lowest possible Mach number to minimize power requirements and reduce cost. With this in mind, the gust generator design should be optimized to operate with plate 2 at the most acute angle that allows amplitude requirements to be met.

Given that minimizing actuator system amplitude will tend to increase bandwidth, observation two may be made. Plate 1 should be perturbed about a nominal operating point near the extrema of δ_{1-2}. The larger gradient in these regions will provide the best possibility of meeting amplitude and bandwidth requirements.

Variations in total pressure perturbation are shown in Fig. 6. Again, there are two observations. First, the required amplitude may be obtained at values of δ_{1-3} as low as 12 deg. This is much lower than the value required for Mach perturbations. Therefore, in designing the device for a given operating range, it appears sufficient to focus on the amplitude of the Mach perturbation. The second observation is essentially the same observation made in the preceding paragraph. Namely, plate 1 should be operated near the extrema of δ_{1-2}, where the gradients are larger.

The change in the direction of flow from regions 3 to 4, δ_{3-4}, is shown in Fig. 7. Note that changes in the direction of flow during a perturbation are minimized by operating plate 1 near either end of its range. Also, note that the nonuniformity between regions 3 and 4 may be reduced by operating the device at more acute total turning angles.

Figures 8 and 9 show how the length ratios L_1/h and L_{2a}/h vary as a function of deflection angles δ_{1-2} and δ_{1-3}. As with earlier results, these plots support operating plate 1 at the lowest possible value of M_1 and δ_{1-3}. However, unlike the earlier plots, these results suggest that plate 1 should be perturbed about an operating point strictly near $\delta_{1-2} = \delta_{1-3}$. It is near this point that the plate lengths and, thus, moments of inertia, are minimized. Therefore, when $\delta_{1-2,\mathrm{nom}} \cong \delta_{1-3}$, the bandwidth ought to be the greatest.

Bandwidth Estimation

The results presented in Figs. 5–9 show that the new gust generator could be designed to meet six of the seven gust generator requirements listed in Table 1. The only requirement not quantitatively addressed, the bandwidth requirement, will be discussed in this section.

An actuator system is needed to assess whether or not the new gust generator can meet bandwidth requirements. Before that, a detailed structural analysis ought to be performed. The structural analysis should minimize weight while maintaining high strength and stiffness. Because these detailed analyses are outside the scope of this study, a number of assumptions were made. In lieu of an actuator system design, the actuator system for the gust plate is used to estimate the bandwidth of the new gust generator. The new device was designed using the same thickness and bevel angles as the original gust plate. However, four different materials were considered as structural materials for the new gust generator.

A new gust generator design that meets the previously specified requirements is detailed by Melcher.[7] Nominal values for this configuration are $M_1 = 3.274$, $\delta_{1-2,\mathrm{nom}} = 14.4$ deg, $\delta_{1-3,\mathrm{nom}} = 16.4$ deg. Other geometric parameters resulting from the design process are given in Tables 2 and 3. To complete the design, an amplitude was needed for the change in angle of plate 1. During the design process,

Table 2 Geometric design parameters for plate 1

Parameter	Value
Leading-edge bevel	15 deg
Trailing-edge bevel	15 deg
Plate length	91.68 cm
Plate thickness	3.89 cm
Leading-edge width	266.47 cm
Trailing-edge width	197.61 cm
Lower surface area	2.128 m^2
Plate volume	0.070 m^3
Center of mass	44.18 cm

Table 3 Geometric design parameters for plate 2

Parameter	Value
Leading-edge bevel	15 deg
Trailing-edge bevel	15 deg
Plate length	127.92 cm
Plate thickness	3.89 cm
Leading-edge width	197.61 cm
Trailing-edge width	50.80 cm
Lower surface area	1.589 m^2
Plate volume	0.055 m^3
Center of mass	53.89 cm

Table 4 Plate 1 parameter values for four different structural materials

Parameter	SS	Ti	Al	Gr
Density,				
kg/m^3	7889	4567	2768	1384
(lb/in^3)	(0.285)	(0.165)	(0.100)	(0.050)
Weight,				
N	550	318	193	96
(lb)	(1211)	(701)	(425)	(213)
I_{hinge},				
N · m^2	1499	868	526	263
(lb · ft^2)	(3628)	(2100)	(1273)	(636)
I_{cm},				
N · m^2	283	164	99	50
(lb · ft^2)	(684)	(396)	(240)	(120)

an amplitude of ±2 deg was selected to provide required changes in Mach number and total pressure. That same value is used in this section to compute bandwidth estimates.

To provide an estimate of the frequency bandwidth, it was necessary to compute the mass moment of inertia for both the gust plate and plate 1 of the proposed device. The mass moment of inertia is a measure of resistance to rotational acceleration. The mass moment of inertia for the gust plate is 1.86×10^7 N · c^2 squared (4503 lb · ft^2). Table 4 shows values for the mass moment of inertia of plate 1 when composed of stainless steel (SS), Ti, Al, and a typical graphite composite (Gr). The mass moments of inertia were computed using equations that describe the surface of the plate, including the effect of the leading- and trailing-edge bevels. The moments of inertia shown for each of the four materials are for two axes of rotation. The first axis of rotation, point B in Fig. 3, is the hinge line where the two connected plates touch. Consideration is also given to a second axis parallel to the hinge line. This axis is located 7 cm (2.75 in.) above the center of mass, that is, the same location as the gust plate. It was considered because rotation about the center of mass yields the minimum mass moment of inertia and should yield the highest frequency bandwidth. It is also likely that the center of pressure will be near this point, which will minimize any aerodynamic moments. Note that for plate 1 to rotate about the second axis, the two plates must be physically disconnected. A study should be performed on this configuration to evaluate the interaction of the plates with the flow.

Estimates of the frequency bandwidth were obtained by considering the angular sinusoidal perturbation of plate 1 about the axes defined earlier. Equation (2) describes the angular position of the plate as a function of time. Equations (3) and (4) describe the angular velocity and the angular acceleration, respectively:

$$\Theta(t) = A\sin(\omega t) \tag{2}$$

$$\dot{\Theta}(t) = A\omega\cos(\omega t) \tag{3}$$

$$\ddot{\Theta}(t) = -A\omega^2\sin(\omega t) \tag{4}$$

A maximum value for these parameters may be calculated as shown in Eqs. (5–7) using values for the gust plate:

$$\Theta_{\max} = A = \tfrac{1}{2}\text{ deg} = 8.7267 \times 10^{-3}\text{ rad} \tag{5}$$

$$\dot{\Theta}_{\max} = A\omega_{\max} = 0.65797\text{ rad/s} \tag{6}$$

$$\ddot{\Theta}_{\max} = A\omega_{\max}^2 = 49.610\text{ rad/s}^2 \tag{7}$$

Here, 75 rad/s (12 Hz) is used as the value for maximum excitation frequency. This is the highest frequency reported by Wasserbauer and Whipple.[2]

For the flat plate in question, Eqs. (8) and (9) show the relationship of the angular velocity, angular acceleration, and moment of inertia to angular momentum and torque:

$$H = I_{yy}\dot{\Theta}_y \tag{8}$$

$$\dot{H} = I_{yy}\ddot{\Theta}_y \tag{9}$$

Combining the equations with values from Eqs. (5–7) and Table 4, maximum values for the angular momentum and torque may be computed:

$$H_{\max} = I_{gp}\dot{\Theta}_{\max} = 1224\text{ N}\cdot\text{m}^2/s \tag{10}$$

$$\dot{H}_{\max} = I_{gp}\ddot{\Theta}_{\max} = 92{,}275\text{ N}\cdot\text{m}^2/\text{s}^2 \tag{11}$$

Assuming the actuator system can provide the level of angular momentum and angular acceleration specified in Eqs. (10) and (11), it is then possible to determine the maximum frequency that may be attained with the proposed gust generator design. Equations (12–14) show the formulas needed to calculate the results displayed in Table 5:

$$A = 2\text{ deg} = 3.4907 \times 10^{-2}\text{ rad} \tag{12}$$

$$\omega_{\max}(H_{\max}) = 2\pi f_{\max}(H_{\max}) = H_{\max}/(A\cdot I_{yy}) = 35{,}065/I_{yy} \tag{13}$$

$$\omega_{\max}(\dot{H}_{\max}) = 2\pi f_{\max}(\dot{H}_{\max}) = \sqrt{\dot{H}_{\max}/(A\cdot I_{yy})} = 1626\Big/\sqrt{I_{yy}} \tag{14}$$

Table 5 Estimates of frequency bandwidth for various structural materials and axis of rotation

Frequency	SS	Ti	Al	Gr
Axis 1 (hinge line)				
$\omega_{\max} = F(H_{\max})$,				
rad/s	23	40	67	133
(Hz)	(4)	(6)	(11)	(21)
$\omega_{\max} = F(\dot{H}_{\max})$,				
rad/s	42	55	71	100
(Hz)	(7)	(9)	(11)	(16)
Axis 2 (center of mass)				
$\omega_{\max} = F(H_{\max})$,				
rad/s	124	214	354	701
(Hz)	(20)	(34)	(56)	(112)
$\omega_{\max} = F(\dot{H}_{\max})$,				
rad/s	97	127	163	230
(Hz)	(15)	(20)	(26)	(37)

The data in Table 5 show that, due to torque limitations, the gust plate actuator system cannot drive the new gust generator at frequencies meeting bandwidth requirements. Only one case meets the 70-Hz bandwidth requirement. That case requires that the gust generator be made of Gr that plate 1 be rotated about an axis near the center of mass, and that the bandwidth be limited by angular momentum instead of torque. Part of the reason that there is not a more significant increase in bandwidth is that increases due a smaller moment of inertia are offset by requirements for larger amplitude.

Rather than suggesting that the proposed gust generator will not work, the data in Table 5 highlight the need for a high-speed actuator designed specifically for this application. However, if an actuator system design that provides suitable frequency response for a single oscillating plate proves to be unfeasible, it is possible to further reduce the inertia of plate 1 by dividing it widthwise into several independently actuated sections. The resulting increase in bandwidth will not come without a price. To maintain a uniform flowfield, the actuator control must move all plate sections in phase throughout the required frequency domain.

An analysis of the other operational modes is in progress and some results have been published.[9]

Concluding Remarks

This work was motivated by need for an experimental device to test control systems for high-speed inlets. Over the past 40 years, a number of devices have been investigated for their ability to generate high-frequency gustlike perturbations in supersonic flow. To date, no device has been found that meets requirements that were defined in the late 1970s. The purpose of this research was to propose and investigate the feasibility of a new gust generator, the dual plated disturbance generator. The study focused primarily on aspects of the problem related to the fluid mechanics, although some mechanical design considerations were also taken into account. One of four possible modes of operation was investigated. In the mode considered, the plates are oriented in supersonic flow so that they create two oblique shocks. Oscillating the upstream plate while the position of the downstream plate remains fixed produces inlet perturbations with desired properties.

The results in this paper show that, under certain conditions, the proposed device can meet the gust generator requirements based on geometry and flowfield considerations. They also show that the structural and actuator system designs, needed to determine whether the device will meet bandwidth requirements, are warranted.

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