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13E TRANSONIC BUFFET OF A SUPERCRITICAL AIRFOIL

Reported by
X.Z. Huang
of work by

INTRODUCTION

This investigation was carried out in the Institute for Aerospace Research (IAR) 2D High Reynolds Test Facility (Ref. 1 to Ref. 3 and Fig. 1) to study the buffet characteristics of a supercritical airfoil, BGK No. 1 (Fig. 2). Steady, unsteady surface pressure and normal force were measured at various angles of attack and Mach numbers. The statistical properties of the normal force and pressure were carried out by spectral analyses. Buffet onset boundaries were evaluated from the divergence of the fluctuating normal force while buffet intensities were determined from the normal force measurements. The attached and separated flow regions on the airfoil as well as the merging of a shock induced separation bubble with the trailing edge separation region were determined by skin friction measurements.

The test program is presented in Table 1. There are two BGK No.1 models. One has normal static pressure orifices and 6 pressure ports to measure pressure fluctuations (BGK-1). Another has 15 fast response transducers (BGK-1(m)). The model’s coordinates and the locations of pressure orifices and transducers are listed in Table 2 Table 3 respectively (in CD ROM). The experimental arrangement and results have been described in detail in Ref. 4 to Ref. 9. Tabulated data and illustrations are presented in Table 4 to Table 7 and Fig. 3 to Fig. 16 in CD ROM with part of the illustrations shown here.

Fig. 3 and Table 4 show the fluctuating normal force on BGK-1 model for various Mach numbers. Typical power spectra of the normal force are shown in Fig. 4. The frequencies of the shock motion vary from 70-80 Hz for the Mach number range of 0.688-0.796 and are partly listed in Table 5. The flow conditions where discrete shock oscillations were detected are summarized in Fig. 5. The test program for BGK-1(m) in Table 1 can be sorted in three cases as seen in Fig. 5: 1) points A, B, C, D, and E; 2) points a, b, c, d and e; and 3) points 1, 2, 3, 4, and 5 respectively. The shaded region was obtained by fixing a Mach number but varying the incidence in the experiment. A power spectra plot of the normal force was computed at each α and the presence of shock waves was determined from observing whether the 70-80 Hz peak was present or not. The buffet boundary, which was obtained from divergence of the fluctuating normal force, is included in this figure for reference. This buffet onset is identified from the divergence of the normal force fluctuations by noting the point on the curve with a slope dCN/dCL=0.1. This value is arbitrarily chosen, but in those cases where buffet onset is primarily due to trailing edge separations, this criterion for deriving the buffet boundary is found to give consistent results and agrees with values computed from trailing edge pressure divergence.

The static surface pressure distributions are listed in Table 6 with some examples shown here from Fig. 6 to Fig. 8. The cross-hatched and open bar symbols in Fig. 7 and Fig. 8 denote regions of attached and separated flows determined from skin friction measurements.

Table 7 presents the unsteady pressure or the pressure intensities along airfoil chord of BGK-1 and BGK-1(m) models. The corresponding figures are shown in Fig. 10 and Fig. 11.

The statistical properties such as power and cross power spectral density, auto and cross correlation functions, as well as coherence functions of pressure and normal force have been measured at different Mach numbers and angles of attack. As examples Fig. 12 shows a set of the spectral analyses at the condition of M=0.753 and α=5.66° for BGK-1 model. The frequency response of the installed transducers was calibrated and established to be flat up to approximately 200 Hz. The normal force signal was obtained at the sampling frequency of 1.6 kHz. Power spectra of unsteady pressure on upper surface of BGK-1(m) at different locations are shown from Fig. 13a to Fig. 13c. Fig. 14 shows the cross correlation functions between different transducers at M=0.688 and α=3.99°, 6.43° and 9°.

The pressure-time histories on BGK-1(m) model at M=0.71 and various α are presented in Fig. 15. The unsteady pressure fluctuations behind the periodic shock wave have two contributions. One is from a random component associated with the turbulent motion in the separated flow region. Another is a deterministic part from the pressure field as a result of shock wave oscillation. Thus, approximately 175 ensemble averages of the pressure signals were performed. Each ensemble, which was synchronized to the zero crossings decided from balance normal force spectra, had 32 samples. A Fourier analysis was then performed to obtain the fundamental and harmonics of the oscillatory pressure field.
For supercritical airfoils such as the BGK No. 1, it is found that at the lower Mach number range, separation can occur behind the shock wave as a bubble and propagates downstream as the angle of incidence is increased. Trailing edge separation can occur at the same time and it moves upstream and the two separated regions will eventually merge. An investigation on the model was carried out at $M=0.688$ using a Preston tube to measure the skin friction on the surface at various angles of attack. The typical distributions of the skin friction coefficient are presented in Fig. 16. The results show that at $\alpha=4.67^\circ$, a small separation bubble begins to form behind the shock wave. The separation bubble grows as the incidence increased and at $\alpha=6.15^\circ$, trailing edge separation has already begun and has moved to nearly 90% of the chord as seen in Fig. 16.

**LIST OF SYMBOLS AND DEFINITIONS**

\begin{itemize}
  \item $b$ \hspace{1cm} model span
  \item $c$ \hspace{1cm} model chord
  \item $C_L$ \hspace{1cm} lift coefficient \hspace{1cm} $= \frac{L}{qbc}$
  \item $C_L^{des}$ \hspace{1cm} design lift coefficient
  \item $C_N$ \hspace{1cm} normal force coefficient \hspace{1cm} $= \frac{N}{qbc}$
  \item $C_p$ \hspace{1cm} pressure coefficient \hspace{1cm} $= \frac{P-P_\infty}{q}$
  \item $\overline{C_p}$ \hspace{1cm} ensemble-averaged pressure coefficient
  \item $C_p'$ \hspace{1cm} fluctuating pressure coefficient \hspace{1cm} $= \frac{P_{rms}}{q}$
  \item $C_N'$ \hspace{1cm} fluctuating normal force coefficient \hspace{1cm} $= \frac{N_{rms}}{qbc}$
  \item $f$ \hspace{1cm} frequency
  \item $L$ \hspace{1cm} lift
  \item $M$ \hspace{1cm} free stream Mach number
  \item $M_{des}$ \hspace{1cm} design Mach number
  \item $M_{dr}$ \hspace{1cm} drag rise Mach number
  \item $N$ \hspace{1cm} Normal force
  \item $\overline{N}$ \hspace{1cm} time-averaged normal force
  \item $N_{rms}$ \hspace{1cm} rms value of normal force \hspace{1cm} $N_{rms}=\sqrt{\lim_{T \to \infty} \frac{1}{T} \int_0^T (N-\overline{N})^2(t)dt}$
  \item $P$ \hspace{1cm} local static pressure
  \item $P_\infty$ \hspace{1cm} free stream static pressure
  \item $\overline{P}$ \hspace{1cm} time-averaged pressure
  \item $P_{rms}$ \hspace{1cm} rms value of the fluctuating pressure \hspace{1cm} $P_{rms}=\sqrt{\lim_{T \to \infty} \frac{1}{T} \int_0^T (P-\overline{P})^2(t)dt}$
  \item $Q,q$ \hspace{1cm} free stream dynamic pressure
\end{itemize}
Re Reynolds number based on chord

\[ R_x(t) = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} x(t) \cdot x(t + \tau) dt \]

\[ R_{xy}(t) = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} x(t) \cdot y(t + \tau) dt \]

\[ S_x(f) = \frac{1}{2 \pi} \int_{-\infty}^{\infty} \left| \overline{X(f)} \right|^2 \overline{X(f) e^{-2\pi i f \tau}} d\tau \]

\[ S_{xy}(f) = \frac{1}{2 \pi} \int_{-\infty}^{\infty} \left| \overline{X(f)} \right|^2 \overline{X(f) e^{-2\pi i f \tau}} d\tau \]

\[ \gamma_{xy}^2 = \frac{S_{xy}(f)}{S_x(f) S_y(f)} \]

\[ \tau \] time delay

**FORMULARY**

1 **General Description of model**

1.1 Designation Bauer-Garabedian-Korn (BGK No. 1) airfoil

1.2 Type Aft-loaded, natural laminar flow-capable, shock-free supercritical airfoil

1.3 Design condition Potential flow

1.4 Additional remarks

1.5 References Ref. 10

2 **Model Geometry**

2.1 Chord length 10 in

2.2 Span 15 in

2.3 Model coordinate See Table 2 in CD ROM

2.4 Nose radius -

2.5 Maximum thickness \( t/c = 11.8\% \)

2.6 Trailing edge thickness 0.1% of the chord

2.7 Additional remarks

2.8 References Ref. 4, 10

3 **Wind Tunnel**

3.1 Designation IAR 2D High Reynolds Test Facility

3.2 Type of tunnel Blowdown, closed test section

3.3 Test section dimensions Rectangular, height 60 in, width 15 in, (see Fig. 1a)
3.4 Length of parallel section 141 in.
3.5 Floor and ceiling porosity 20.5%
3.6 Side wall boundary layer A gap between inlet and nozzle section permit bleeding into the plenum chamber of fairly thick side wall boundary layer (~2 in.), see Fig. 1b.
3.7 Side wall near model area Additional porous with boundary layer suction to atmospheric, see Fig. 1c.
3.8 Ventilation geometry See Fig. 1d.
3.9 Range of Mach numbers 0.1 to 1.1
3.10 Re 40x10⁶/ft at M=1, 10 seconds total run time
3.11 Wake traverse probe 7 wafer (12 ports) Statham miniature transducer unit
3.12 Turbulence intensity level 0.1% for Re/ft ≤ 6x10⁶
0.16–0.24% for Re/ft 10x10⁶–27x10⁶
3.13 Turbulence intensity level 0.1% for Re/ft ≤ 6x10⁶
0.16–0.24% for Re/ft 10x10⁶–27x10⁶
3.14 Reference on tunnel Ref. 1, 2 and 3

4 Measurements and Observations
4.1 Steady pressure for the mean conditions measured directly
4.2 Unsteady pressure for the mean conditions measured directly
4.3 Steady forces for the mean conditions measured directly
4.4 Unsteady forces for the mean conditions measured directly
4.5 Spectral analysis of the pressure yes.
4.6 Spectral analysis of the loads yes
4.7 Local skin friction yes
4.8 Buffet boundaries yes
4.9 Synchronous Cp time histories yes

5 Test Conditions
5.1 Tunnel height/model chord ratio 6
5.2 Tunnel width/model chord ratio 1.5
5.3 Range of Mach number 0.501 – 0.805
5.4 Incidence range -0.36 – 11.74
5.5 Reynolds number range 15x10⁶ – 20x10⁶
5.6 Range of tunnel total pressure 300 psi
5.7 Maximum mass flow 10 lbm/sec
5.8 Definition of model incidence between “x” of model axis (Fig. 2) and tunnel axis
5.9 Position of transition, if free Not applicable
5.10 Flow instabilities during tests No evidence
5.11 Model deformation under the loads Negligible
5.12 References describing tests Ref. 4 to Ref. 9

6 Instrumentation
6.1 Steady pressure measurements for BGK-
1 model

6.1.1 Location of orifices
Position of orifices See Fig. 2a and Table 3 in CD ROM
6.1.2 Type of measuring system
Type of measuring system 70 pressure tubes + 15 in situ pressure transducers

6.2 Unsteady pressure measurements for model BGK-1

6.2.1 Location of transducers
Location of transducers See Fig. 2a (in the middle chord) and Table 3 in CD ROM
6.2.2 Type of transducers
Type of transducers 6 Kulite TQ 360 25 psid transducers
6.2.3 Dynamic response
Dynamic response Flat up to approximately 200 Hz.
6.2.4 Signal record
Signal record Recorded on FM tape for subsequent analysis.
6.2.5 Data reduction

6.3 Unsteady pressure measurement for model BGK-I(m)

6.3.1 Location of transducers
Location of transducers See Fig. 2b and Table 3 in CD ROM
6.3.2 Type of transducers
Type of transducers 16 of 25 psid custom made CQ-062-25D differential Kulite transducers
6.3.3 Diameter of screen
Diameter of screen 0.042 in.
6.3.4 Type of screen
Type of screen 0.005 in thick with 0.062 in diameter holes in a mesh pattern
6.3.5 Signal measurements
Signal measurements Signals were filtered by a four pole low pass filter having a 300 Hz 3db point and a –24 db/octave slope beyond 600 Hz.
6.3.6 Sampling rate
Sampling rate 1.6 kHz

6.4 Loads measurement

6.4.1 Type of sensors
Type of sensors strain gages
6.4.2 Balance
Balance 3 component side balance with max capacity of N=20,000 lbf, m=22,500 in.lb and X=2,000 lbf
6.4.3 Pitch drive system
Pitch drive system Range: 55°
maximum angular rate: 12°/sec, fully loaded
step program: 0.25°, 0.5°, 1°, 2°, 5°
ramp program: 0° – 10°/sec
6.4.4 Sampling rate
Sampling rate 1.6 kHz

6.5 Skin friction measurement

6.5.1 Type of transducers
Type of transducers Given by the difference between the total and static pressures
6.5.2 Method of measurement
Method of measurement Preston tube to determine the pitot pressure
6.5.3 Spatial resolution
Spatial resolution 0.05c for x > 0.6c and 0.02c for x < 0.6c respectively

7 Data presentation

7.1 Test cases
Test cases See Table 1
7.2 Normal force fluctuation
Normal force fluctuation Fig. 3, Fig. 4 and Table 4 in CD ROM
7.3 Shock oscillation frequencies
Shock oscillation frequencies Table 5 in CD ROM
7.4 Region of shock oscillation
Region of shock oscillation Fig. 5
7.5 Steady pressure
Steady pressure Fig. 6 to Fig. 9 and Table 6 in CD ROM
7.6 Unsteady pressure
Unsteady pressure Fig. 10, Fig. 11 and Table 7 in CD ROM
7.7 Spectral analysis
Spectral analysis Fig. 12, Fig. 13 and Fig. 14
7.7.1 Power spectral density
Power spectral density Fig. 12a and Fig. 13
7.7.2 Auto correlation functions Fig. 12b
7.7.3 Cross correlation functions Fig. 12c and Fig. 14
7.7.4 Cross power spectral density Fig. 12d
7.7.5 Coherence function Fig. 12e
7.7.6 Cross power spectral density and coherence function between pressure and normal force Fig. 12f
7.7.7 Pressure-time histories Fig. 15
7.8 Skin friction Fig. 16
7.9 Example illustrations of results Fig. 6, Fig. 7, Fig. 8, Fig. 10 to Fig. 16

8 Comments on data
8.1 Mach number Mach number be maintained constant by control system measured by a potentiometer
8.2 Steady incidence measured by a potentiometer
8.3 Balance linearity maximum 0.3% and generally < 0.1%
8.4 Balance interaction <1.26%
8.5 Balance natural frequencies 140, 215, 320, 360 Hz, buffet excitation frequencies=70-80 Hz
8.6 Unsteady pressure coefficients a discrete frequency of ≈420 Hz was detected due to tunnel disturbances (See Fig. 4)
8.7 Wall interference corrections distributed suction was applied through porous plates in the vicinity of the model to minimize any three-dimensional effects

9 Personal contact for further information
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10 List of references
Table 1 Test matrix

<table>
<thead>
<tr>
<th>$M_\infty$</th>
<th>$R_e \times 10^6$</th>
<th>$\alpha^\circ$</th>
<th>$C_L$</th>
<th>Model</th>
<th>Cases in Fig. 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.501</td>
<td>21.0</td>
<td>11.74</td>
<td>1.124</td>
<td>BGK-1</td>
<td></td>
</tr>
<tr>
<td>0.703</td>
<td>21.3</td>
<td>-0.31, 6.77, 8.71</td>
<td>0.278, 1.077, 1.02</td>
<td>BGK-1</td>
<td></td>
</tr>
<tr>
<td>0.753</td>
<td>21.1</td>
<td>5.66</td>
<td>0.945</td>
<td>BGK-1</td>
<td></td>
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<tr>
<td>0.775</td>
<td>15.3</td>
<td>2.55, 3.57, 4.61</td>
<td>0.762, 0.859, 0.858</td>
<td>BGK-1</td>
<td></td>
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<td>0.783</td>
<td>21.0</td>
<td>-0.34, 2.55, 3.55, 4.57, 5.60, 6.61</td>
<td>0.304, 0.756, 0.807, 0.820, 0.827, 0.84</td>
<td>BGK-1</td>
<td></td>
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<td>0.805</td>
<td>20.9</td>
<td>-0.36, 3.52</td>
<td>0.314, 0.727</td>
<td>BGK-1</td>
<td></td>
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<tr>
<td>0.597</td>
<td>20.0</td>
<td>5.95</td>
<td></td>
<td>BGK-1(m)</td>
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</tr>
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<td>0.688</td>
<td>20.0</td>
<td>3.99, 4.95, 6.43, 6.94, 9.0</td>
<td>0.981, 1.052, 1.059, 1.052, 1.069</td>
<td>BGK-1(m)</td>
<td>A, B, C, D, E</td>
</tr>
<tr>
<td>0.688</td>
<td>20.0</td>
<td>3.99, 4.45, 4.67, 4.95, 5.16, 5.44, 5.65, 5.92, 6.15, 6.43, 6.67</td>
<td></td>
<td>BGK-1(m)</td>
<td>skin friction</td>
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<td>0.71</td>
<td>20.0</td>
<td>-0.316, 1.396, 3.017, 4.905, 6.97</td>
<td>0.322, 0.610, 0.886, 1.034, 1.016</td>
<td>BGK-1(m)</td>
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<td>0.722</td>
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<td>0.747</td>
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<td>BGK-1(m)</td>
<td>d</td>
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<td>6.04</td>
<td></td>
<td>BGK-1(m)</td>
<td>e</td>
</tr>
</tbody>
</table>
Fig. 1a  IAR 15 in x 60 in 2-D insert

Fig. 1b  Downstream view of 2-D insert
300 psi air supply (4" pipe dia.)

Diffuser

Cover plates

Fig. 1c 2D section arrangement for IAR 5ft x5ft wind tunnel

Exhaust diffuser

Model module

8" pipe

Suction box

Slide valve

Mounting pins

Enlarged view on AA

Fig. 1d Suction arrangement
Location of pressure orifices for static pressure measurements

Location of pressure ports for fluctuating pressure measurements

2a BGK-1 model

Fig. 2 BGK No. 1 supercritical airfoil

2b BGK-1(m) model

Fig. 3 Variation of the fluctuating normal force coefficient with Mach number and steady state lift coefficient

Fig. 4 Power spectra of normal force

Fig. 5 Region of shock oscillation
Fig. 6 Steady pressure distributions
Fig. 6 (cont.) Steady pressure distributions

6g $M=0.804, \alpha=3.54^\circ$

6h $M=0.804, \alpha=0.33^\circ$

Fig. 7 Steady pressure distributions on upper surface at $M=0.688$

Fig. 8 Steady pressure distributions on upper surface at various Mach numbers
Fig. 10 Variation of pressure intensities along airfoil chord

Fig. 11 Unsteady pressure distributions
Fig. 12a  Power spectral density for $M_\infty=0.753$, $C_L=0.945$, $q=24.5$ psi

Fig. 12b  Auto correlation functions for $M_\infty=0.753$, $C_L=0.945$, $q=24.5$ psi
Fig. 12c  Cross correlation functions for $M_\infty = 0.753$, $C_L = 0.945$, $q = 24.5$ psi
Fig. 12d Cross power spectral density for $M_\infty=0.753$, $C_L=0.945$, $q=24.5$ psi
Fig. 12d (cont.) Cross power spectral density for $M_a=0.753$, $C_L=0.945$, $q=24.5$ psi
Fig. 12c  Coherence functions for $M_\infty=0.753$, $C_L=0.945$, $q=24.5$ psi
Fig. 12f Cross power spectral density and coherence function between pressure and normal force for $M_a=0.753$, $C_L=0.945$, $q=24.5$ psi
13a transducers located before and after shock

13b transducers located in the separation bubble

13c transducers located in the attachment and trailing-edge separation regions

Fig. 13 Power spectra of pressure on upper surface

14a M = 0.688, α = 3.99°

14b M = 0.688, α = 6.43°

14c M = 0.688, α = 9°

Fig. 14 Cross-correlation functions of pressure
Fig. 15 Pressure-time histories at $M=0.71$ and various $\alpha$

Fig. 16 Skin friction coefficient at $M=0.688$ and various $\alpha$