The influence of compliant surfaces on bypass transition

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Abstract The objective of the work was to investigate the effect of compliant surfaces on the receptivity and bypass transition of a boundary layer. Hot wire measurements in the pre-transitional and transitional boundary layers on nine different compliant and one rigid surface with identical geometries were made. The experiments were conducted in air and the compliant surfaces were manufactured from gelatine covered by a 10 μm protective PVC film. The laminar boundary layer profiles and growth rate results were the same for all the surfaces. However, the receptivity of the laminar boundary layer to freestream disturbances increased close to the leading edge of each compliant surface. Further downstream the majority of the compliant surfaces were successful in reducing the receptivity to a value below that for the rigid surface. The transition onset position on the compliant surfaces ranged from 3% downstream to 20% upstream of the rigid surface position. It was concluded that compliant surfaces with optimum properties can reduce receptivity and delay transition.

List of symbols

- $A_m$: contact area between test mass and compliant surface
- $c$: correction factor in measurement of compliant surface properties
- $E$: Young’s modulus for compliant surface
- $E_d$: Young’s modulus from dynamic measurement
- $E_s$: Young’s modulus from static measurement
- $g$: gravitational acceleration
- $\text{Gain}_{\text{NW}}$: near wall gain
- $L$: thickness of compliant surface
- $m$: test mass
- $Re_x$: Reynolds number based on $U$ and $x$
- $Re_{es}$: $Re_x$ at start of transition
- $Re_0$: Reynolds number based on $U$ and $\theta$
- $t$: time
- $Tu$: freestream turbulence level
- $u$: air velocity
- $u_{\text{rms}}$: rms fluctuating air velocity
- $U$: freestream air velocity
- $U_{\text{rms}}$: rms fluctuating freestream velocity
- $x$: streamwise distance
- $y$: wall normal distance
- $z(t)$: displacement of compliant surface
- $z_i$: displacement amplitude of the $i$th cycle
- $z_0$: maximum displacement amplitude
- $\Delta z$: deformation of compliant surface
- $\delta$: boundary layer thickness
- $\phi$: initial phase angle
- $\Gamma$: system damping factor
- $\lambda$: Pohlhausen pressure gradient parameter
- $\lambda_s$: turbulence length scale
- $\nu$: kinematic viscosity
- $\theta$: boundary layer momentum thickness
- $\rho$: density of air
- $\rho_{cs}$: density of compliant surface
- $\omega_n$: natural frequency of compliant surface/mass system
- $\omega_d$: damped frequency
- $\zeta$: damping coefficient for compliant surface material

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1 Introduction

For many years engineers have recognised the huge potential for energy savings that can be realised if a significant reduction in aerodynamic drag can be achieved. In many engineering situations if the turbulent boundary layers on a body, such as an aircraft, could be replaced by laminar ones, the drag could be reduced by at least 50%. To achieve this, boundary layer transition must be prevented.

Drag reduction techniques are either passive (e.g. compliant surfaces or riblets) or active (e.g. plasmas or suction). Passive devices have only resulted in very modest drag reduction to date, although in theory for transition induced by Tollmein Schlichting (T–S) instability, compliant surfaces have the capability of delaying transition indefinitely (Carpenter and Garrard 1985; Carpenter 1993; Davies and Carpenter 1997; Choi et al. 1997; Gad-el-Hak et al. 1984; Yeo 1986). Active devices are more successful, but because the devices themselves consume significant energy and the devices are more expensive, the overall cost benefit is often marginal. Research into drag reduction is still very active though and as the mechanisms associated with transition and turbulence production become better understood, engineers are able to design systems which are more effective in reducing drag. The various types and advantages of compliant surfaces are discussed by Gad-el-Hak (1998).

The majority of work on compliant surfaces (Carpenter and Garrard 1985; Carpenter 1993; Davies and Carpenter 1997; Choi et al. 1997; Gad-el-Hak et al. 1984; Yeo 1986) has only considered how compliant surfaces can suppress T–S waves. T–S waves are only observed for freestream turbulence levels less than 1%, which is generally the case for flow over aircraft. Little attention has been paid to bypass transition, which occurs at higher freestream turbulence levels. In practice, the flow mechanisms associated with T–S wave transition and bypass transition are present in all flows. T–S waves are suppressed at low boundary layer Reynolds numbers, but once a critical Reynolds number is exceeded, growth is exponential. The boundary layer fluctuations associated with bypass transition grow linearly with the boundary layer thickness and are proportional to the level of freestream turbulence. If the T–S waves are suppressed by a compliant surface, then transition will still occur due to a bypass mechanism when the fluctuations have grown linearly to the critical amplitude. This therefore seems to be the likely reason why compliant surfaces designed to suppress T–S waves indefinitely are still unsuccessful in preventing transition. Recent results, Fransson et al. (2006), suggest that using roughness elements to generate weak fluctuation streaks, similar to those observed in bypass transition, can actually suppress T–S mode transition, although ultimately transition will occur through the bypass mechanism.

The objective of the current work was therefore to determine the effect of different compliant surfaces on bypass transition through hot wire experiments to determine the boundary layer receptivity and transition onset position.

2 Experimental method

The experiments were conducted in the 1,050 mm long by 310 mm wide by 155 mm high outlet section of a blower wind tunnel (see Fig. 1). The test plate, which has a 6:1 elliptic leading edge and is of 15 mm thickness was located at mid-height within the test section. Morkovin (1969) stated that for transition to occur through a bypass rather than a T–S mode, the freestream turbulence level Tu must exceed 1%. For this reason, the tunnel freestream turbulence level was increased from the natural level of about 0.3–1.8% at the leading edge using a grid (square mesh of 1.2 mm diameter wires 12 mm apart) placed 432 mm (36 mesh pitches) upstream of the leading edge. The integral length scale for the freestream turbulence at the leading edge was estimated as 4.6 mm using the Roach (1987) correlation.

The measurements were made using a DISA M system anemometer connected to a single DISA 55P15 boundary layer probe. The probe was traversed using a computer controlled traverse mechanism which was placed over the compliant surface on a cantilever fixed at the trailing edge of the plate. Boundary layer traverses were performed at four streamwise stations at $x = 112, 195, 277$ and 340 mm from the leading edge. Each traverse consisted of at least 30 $y$ location measurements within the boundary layer and a further 10 locations outside the boundary layer up to at least twice the boundary layer thickness, where the unsteady velocity had reached its freestream value.

Fig. 1 Experimental setup
The experimental arrangement was designed such that the environments for the rigid and compliant surface measurements were identical. To this end the symmetrical aluminium test plate had a 4 mm deep × 618 mm long cavity machined in 1 surface 25 mm from the leading edge in which the compliant surface material was placed. The plate could be removed from the tunnel and inverted such that the measurements on both rigid and compliant surfaces were always performed on the upper surface.

2.1 Compliant surface

The compliant surface was made from gelatine which was mixed with hot water, poured into the cavity and allowed to cool. The gelatine was then covered by a 10 μm thick PVC film which was wrapped around the leading and trailing edges of the plate, but was not tensioned. The PVC film was necessary to prevent shrinkage of the gelatine due to water loss, but was sufficiently thin that it did not significantly alter the compliant surface properties. Particular attention was given to achieving a smooth interface between the aluminium plate and the leading edge of the compliant material, by ensuring that the plate was precisely horizontal when the gelatine was poured and the exact volume of gelatine mixture required to fill the cavity was used.

The material properties of the compliant surface were altered by changing the proportions of gelatine and water in the mix. The material properties, which are pertinent here, are the density \( \rho \), the Young’s modulus \( E \) and the damping coefficient \( \zeta \). In the current experiments the density was 1,000 kg/m\(^3\) throughout. The Young’s modulus and damping coefficient were established by measuring the dynamic response of the surface to the load imposed by dropping a 10 or 50 g mass onto the surface from a height of about 20 mm. The mass and hence surface displacement was measured using an optical displacement sensor (Omron LED Z4W-V). The resolution and frequency response of the sensor are 10 μm and 200 Hz, respectively. If it is assumed that gelatine acts as a viscoelastic material, the displacement \( z(t) \) will be given by the equation

\[
z(t) = z_0 \cos(\omega_d t - \phi) \exp(-\Gamma \omega_a t)
\]  

where \( z_0 \) is the maximum displacement amplitude, \( \omega_d \) is the system natural frequency, \( \Gamma \) is the system damping coefficient and \( \phi \) is the initial phase angle.

The damped system frequency,

\[
\omega_d = \sqrt{1 - \Gamma^2 \omega_a}
\]

is obtained from the time elapsed between successive peaks in the displacement.

The system damping coefficient \( \Gamma \) can be determined by comparing the amplitudes of successive peaks \( z_i \) and \( z_{i+1} \) in the signal from the relationship

\[
\Gamma = \frac{\ln(z_{i+1}) - \ln(z_i)}{\sqrt{(2\pi)^2 + \left(\ln(z_{i+1}) - \ln(z_i)\right)^2}}
\]  

The compliant surface material properties can then be determined from the system properties by

\[
E_d = \frac{cmL}{A_m} \left(\frac{\omega_d}{\sqrt{1 - \Gamma^2}}\right)^2
\]

and

\[
\zeta = \frac{2cmL \omega_d}{A_m} \frac{\Gamma}{\sqrt{1 - \Gamma^2}}
\]

where \( c \) is a correction factor, resulting from the non-uniform stress beneath the test mass. \( c \) was determined using the ABAQUS finite element software to compute the static displacement of the mass when placed on the compliant layer.

The Young’s modulus was also measured from a static test using the same mass and the relationship

\[
E_s = \frac{cmgL}{A_m \Delta \zeta}
\]

where \( \Delta \zeta \) is the static deformation of the compliant surface.

The properties of the nine compliant surfaces used in the experiments are given in Table 1. The final column gives the value of the dimensionless quantity used in the analysis of the results.

3 Discussion

3.1 Rigid surface results

Hot wire measurements were first made for boundary layers on the rigid surface, in order that these could be used for benchmark comparisons with the compliant surface results. Traverses were performed at the four streamwise measurement locations within the laminar boundary layer using a variety of tunnel speeds between 3 and 9 m/s. Figure 2 shows the boundary layer development along the plate. As the test section is of constant cross sectional area, the boundary layer blockage leads to a slightly favourable streamwise pressure gradient, which is approximately given by a Pohlhausen pressure gradient parameter \( \lambda \) of 2 as shown in the figure.
The receptivity of the laminar boundary layer to free-stream fluctuations plays an important role in bypass transition. The receptivity can be quantified using the near wall gain, which was defined and used by Johnson and Ercan (1999) as

\[
\text{Gain}_{NW} = \frac{u_{rms}}{U_{rms}} \times \frac{U}{u} \tag{7}
\]

where \(u\) and \(u_{rms}\) are the mean and rms velocities measured in the near wall region, which is defined as the region between \(y/\delta = 0\) and 0.2, within which the near wall gain is found to be approximately invariant. The experimental uncertainty in the Gain is estimated at 5%. The flow rate within this region in the laminar boundary layer is approximately equal to the flow rate within the laminar sub-layer of a turbulent boundary layer and hence it is this fluid which will ultimately form the laminar sub-layer in the turbulent layer.

Figure 3 shows the near wall gain results for the rigid surface, together with the correlation

\[
\text{Gain}_{NW} = 0.0305Re_x^{1/2} \tag{8}
\]

This relationship therefore implies that the near wall gain is proportional to \(Re_x\), which was also observed by Johnson and Ercan (1999) and is consistent with the deduction of Fransson et al. (2005) that the fluctuation energy \((u_{rms}/U)^2\) in the boundary layer fluctuations (streaks) is proportional to \(Re_x\).

### 3.1.1 Onset of transition

The onset of transition was determined by measuring the variation in the intermittency with tunnel speed at one of the fixed streamwise measurement locations and at \(y/\delta = 0.2\). The position where \(y/\delta = 0.2\) was found at each tunnel speed by moving the hot wire to the location where \(u/\delta = 0.4\), which, for a laminar Blasius boundary layer profile, corresponds to \(y/\delta = 0.2\). The intermittency was then determined in real time using the algorithm developed by Johnson and Fasihfar (1994). Onset of transition was defined here as the condition when the intermittency was 1% and so the tunnel speed was varied until this condition was achieved.

The current results are shown in Fig. 4 along with the correlations due to Mayle (1991), Ercan (1997) and Brandt et al. (2004). The current results are consistent with all these correlations, but there are significant variations between the correlations themselves, which are primarily due to the differing freestream turbulence length scales in the different experiments. In order to use the current results as a benchmark for the compliant surface results, the correlation equation

\[
Re_x = -2.66 \times 10^{11}Tu^3 + 1.17 \times 10^{10}Tu^2 - 1.88 \times 10^8Tu + 1.24 \times 10^6 \tag{9}
\]

was used. This is the least rms error third order polynomial fit to the data, but the form of the equation has no physical relevance.

### 3.2 Compliant surface results

The boundary layer data for the nine compliant surfaces in Fig. 5 shows that there is no significant difference between the boundary layer development on the rigid and compliant surfaces. Typical boundary layer profiles for one of the compliant surfaces are shown in Fig. 6. These match the Blasius profile and hence confirm that the laminar boundary layer development over the compliant surface is essentially identical to that over a rigid one.

### 3.2.1 Receptivity

A dimensional analysis of the problem (Appendix), indicates that the compliant surface properties can be characterised by the dimensionless quantity

<table>
<thead>
<tr>
<th>(E_s (\text{N/m}^2))</th>
<th>(E_d (\text{N/m}^2))</th>
<th>(\zeta (\text{Ns/m}^2))</th>
<th>(\frac{C^2}{Re_x}^{1/2})</th>
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<td>700</td>
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<td>7.17</td>
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<table>
<thead>
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<th>Table 1</th>
<th>Compliant surface material properties</th>
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<td>(E_s (\text{N/m}^2))</td>
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<td>9,900</td>
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The near wall gain was determined for each of the nine compliant surfaces at each of the four measurement stations for a freestream velocity of 6.5 m/s measured at the plate leading edge. The ratios between the compliant and rigid surface gains at each measurement station are shown in Fig. 7. Although there is some experimental scatter in these results the overall trends with change in the compliant surface properties are clear. At the first measurement station, \( x = 112 \text{ mm} \), all the compliant surfaces lead to an increase in receptivity. This is believed to be due to the generation of waves originating from the compliant surface leading edge as described by Hansen et al. (1980) as type 1 waves. Davies and Carpenter (1997) also observed a large increase in disturbance kinetic energy immediately downstream of the leading edge of the compliant surface, although they did not classify these disturbances as type 1 waves. These disturbances were associated primarily with streamwise fluctuations, which is also the observation made in the current work as only the streamwise fluctuations contribute to the gain. The current compliant surfaces fail to damp out these waves close to the leading edge. At \( x = 195 \text{ mm} \), some reduction in receptivity has been achieved though, but all the compliant surfaces still lead to an increase in receptivity compared to the rigid surface. By the third station, \( x = 277 \text{ mm} \), the majority of the compliant surfaces are effective in reducing the gain below that of the rigid surface with the most effective surfaces having a \( \zeta^2/\rho_C L^2 \) of approximately 3–4. The situation is similar at the final station at \( x = 340 \text{ mm} \).

The effect of the compliant surface, which was most effective in reducing receptivity in Fig. 7, on the boundary layer fluctuations through the boundary layer is depicted in Fig. 8. It is clear from this figure that the compliant surface has greatest influence on the fluid closest to it, \( y\sqrt{U_c} < 2 \), as might be expected.

### 3.2.2 Onset of transition

The receptivity results in the previous section suggest that the compliant surfaces should be capable of delaying
transition providing onset occurs significantly downstream of the compliant surface leading edge. In order to confirm this, the probe was moved to the $x = 340$ mm location and intermittency readings were taken for various wind tunnel speeds (9–15 m/s) to cover the full transition zone.

The results for six of the compliant surfaces and the rigid surface are shown in Fig. 9. Additional curves corresponding to the rigid surface results but with 3% larger and 12% smaller $Re_x$ values are also included for guidance.
The results show that for the three surfaces with \( \eta^2/E \rho csL^2 \) between 1 and 4 some delay in transition is observed. The surface \( \eta^2/E \rho csL^2 = 3.49 \) which was also the surface that achieved the largest reduction in gain at this station, delays transition by 3%, based on the average shift in \( R e_i \) through the transition process shown in Fig. 9. In all cases the intermittency evolution with downstream distance follows the relationship derived by Dhawan and Narasimha (1957), which is depicted by the lines in the figure.

### 4 Conclusions

Experiments have been conducted to assess the potential of nine compliant surfaces to reduce receptivity and delay transition. Some surfaces were found to delay transition whereas others promoted it. The main conclusions of the work are that

1. Successful compliant surfaces can be manufactured using gelatine covered with PVC film. A technique for measuring the Young’s modulus \( E \) and damping coefficient \( \eta \) of the compliant material has been devised.
2. The mean velocity profile and laminar boundary layer development rate is the same for compliant and rigid surfaces.
3. The material properties of the compliant surfaces are characterised by the dimensionless quantity \( \eta^2/E \rho csL^2 \).
4. The receptivity of the laminar boundary layer increases for the compliant surface close to its leading edge, but further downstream compliance of the surface leads to a reduction in receptivity.
5. Transition can be delayed by up to 3\% of streamwise distance using a compliant surface where \( \eta^2/E \rho csL^2 \) is about 3.5.

### 5 Appendix: dimensional analysis

The transition process for a boundary layer is governed by the receptivity. For bypass transition the receptivity can be characterised by the near wall gain. For a zero pressure gradient boundary layer on a rigid surface, this will depend on the fluid density \( \rho \), the fluid viscosity \( \mu \), the flow velocity \( U \), the length scale of the freestream turbulence \( \lambda_s \) and the boundary layer thickness \( \delta \). This leads to the dimensionless equation

\[
\text{Gain}_{NW} = f \left( Re_i, \frac{\lambda_s}{\delta} \right)
\]  

(A1)

When the rigid surface is replaced by a compliant one, the properties of the compliant surface must also be included. These are the density \( \rho_{cs} \), the Young’s modulus \( E \), the damping coefficient \( \eta \) and the thickness of the layer \( L \). A further four dimensionless quantities are then formed such that

\[
\text{Gain}_{NW} = f \left( Re_i, \frac{\lambda_s}{\delta}, \frac{\eta^2}{E \rho_{cs}L^2}, \frac{\rho}{\rho_{cs}}, \frac{L}{\delta}, \frac{E}{\rho U^2} \right)
\]  

(A2)

where \( \eta^2/E \rho_{cs}L^2 \) characterises the density, elastic and damping properties of the compliant surface and is used for this purpose in the current paper. The remaining three quantities compare the density, characteristic lengths and stresses, respectively for the compliant surface and fluid.

### References


