Application of laser schlieren technique to study shock-wave boundary-layer interaction flow fields

by

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ABSTRACT

This paper demonstrates the use of a simple laser schlieren technique to study complex flow phenomena such as shock-wave boundary-layer interaction in both two-dimensional and three-dimensional flows. The advantage of using such an instrumentation to study the basic characteristics of separated flows is its cost effectiveness, since it uses only a low cost diode (15 W) laser, and its simplicity and accessibility to study unsteady flows in complex flow geometries where geometrical complications may limit the fabrication of pressure taps/use of pressure transducers. The conventional surface pressure signal acquisition method limits the flow analysis only on the model surface and not above the model surface which may be crucial to gain insight of the various processes involved. Keeping in view this aspect, efforts were channelised to use the schlieren principle with laser as the light source. The use of schlieren effect also allows control over the sensitivity of density gradient signal acquisition that may help in studying the flow in greater detail. An array of 16 very-high-response photodiodes arranged on a 1 mm pitch were used for multichannel measurements. A Halis Axisymmetric Configuration (HAC) model and a 24 degree compression ramp model provided the interactive flow field. All the experiments were performed in the hypersonic wind-tunnel facility at HTG.

Off-surface analysis of the complete interactive flow field is made using the laser schlieren system that measures time-dependent voltage signals representative of the fluctuating density gradient field. The density gradient signals in the vicinity of separation location in three-dimensional flows (Halis Axisymmetric Configuration model) reveals oscillatory nature of both the separation shock and separation bubble and also aids in giving insight of the associated energy levels throughout the interaction. In two-dimensional compression ramp flow, these signals help study the movement of shock-legs in the separation region while the space-time correlation functions inside the separated region reveal the structures moving in the direction of external flow and those moving in opposite direction in addition to any residual effects of shock oscillation. A comparison with previous studies on similar flow situations using voltage signals from pressure transducers, that are considered as footprints of the flow structure above, show similar results that helps to validate the use of this simple technique to study such important flow phenomena in supersonic/hypersonic flows.

1. INTRODUCTION

The shock-wave boundary-layer interaction flows have been studied extensively in the past decades. However, much of the earlier research provided information about mean surface properties and flow field structure. Kistler (Kistler, 1964) was, perhaps, the first to study the intermittent nature of the wall pressure signal which was attributed to the unsteady separation shock wave. During the last decade, more attention has been paid to the related flow field unsteadiness in compression ramp flows (Dolling and Murphy, 1983 and Andreopoulos et al., 1988) and in interaction induced by circular cylinders and blunt fins (Dolling and Murphy, 1983 and Dolling and Narlo, 1987). Their results, although obtained from different flow geometries, exhibited statistical properties that were quite similar to those reported by Kistler (Kistler, 1964). Their research has shown that the large-scale motion of separation shock is caused by its displacement due to the expansion and contraction motion of the separated flow. All these results and observations have been reached using intermittent surface pressure signals.

Optical cross-beam technique has been used by Fisher and Krause(1967)to measure statistical properties of turbulent flow by monitoring the fluctuations in light intensity caused by random fluctuations of the absorption or scattering coefficients. Later Funk and Johnston(1970) showed that in addition to absorption and scattering, index of refraction fluctuations can also produce signal fluctuations. The net change in the index is, across even a strong shock, very small and, therefore, the angular deflection of the light rays is also small(Funk and Johnston,1970). If a knife edge is placed in its path, before the image, the sensitivity of the image can be controlled. Panda(1995) demonstrated the scattering of light phenomena, due to interaction of shock-wave and laser beam, to study the shock unsteadiness in an underexpanded jet. Sajben and Crites(1979) made real-time optical measurements of oscillating shocks in two-dimensional diffuser. Later on, Roos and Bogar(1982) made a comparative study of sensing shock motion with hot-film probe and an optical technique(using shadowgraph system and a line-scan camera) and found that the optical technique definitely responds to shock location alone and yields much more accurate results. Further an optical technique has the added advantage of being non-intrusive.

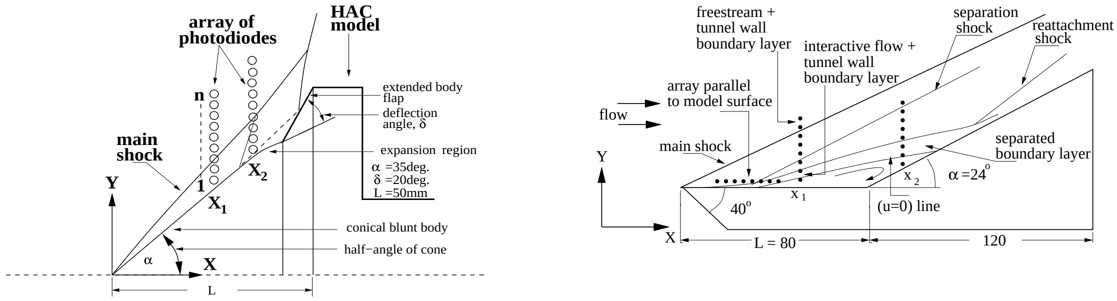
This paper demonstrates the application of a simple laser schlieren technique to study important flow phenomena such as shock-wave boundary-layer interactions on both two-dimensional(ramp model) and three-dimensional(HAC) models to obtain similar results. In fact, due its simplicity and accessibility a point by point detail of the interactive flow field can be obtained using this technique. Off-surface analysis of the complete interactive flow field is made using a Laser Schlieren system that measures time-dependent voltage signals representative of the fluctuating density gradient field. An array of 16 very-high-response photodiodes arranged on a 1 mm pitch were used for multichannel measurements. Verma (Verma, 2002a) and Verma and Koppenwallner (2000,2002b) have already shown the usefulness of this technique in such important flows.

2. WIND-TUNNEL and TEST MODELS

The experiments were performed in the hypersonic wind tunnel at HTG (Hypersonic Technology Göttingen). HTG designed a completely new concept based on the Ludwieg-tube principle implementing state-of-art technologies (Koppenwallner et al. 1993). This wind tunnel is an intermittent blowdown type with a test-section diameter of 250 mm and a variable Mach number capability over the range of Mach 6-11 with maximum run-time of 100 ms.

The results are presented for two test models. One is a three-dimensional Halis Axisymmetric Configuration(HAC) model and the other a two-dimensional 24^o ramp model. The freestream Mach number was $9.68 \pm 2\%$ and $8.94 \pm 4\%$ for HAC and ramp models, respectively. The corresponding freestream

Reynolds number per unit length was $9.26\times10^6\,\mathrm{m}^{-1}$ and $2.078\times10^5\,\mathrm{m}^{-1}$, respectively. To avoid condensation of the relieved flow in the nozzle, the gas column which is ejected during the shot is heated to 773 K±0.2%. Figure 1 shows a schematic of the models used. A data acquisition system that can record up to 32 channels at a speed of up to 40 kHz was used. Piezoresistive pressure gauges installed to measure the flow in the charge tube, test section and vacuum tank were calibrated.



(a) **(b)**

Fig. 1: Schematic of the test models and the experimental procedure followed for flow field analysis in each case (all dimensions are in mm)

(a) Halis Axisymmetric Configuration (HAC) model

(b) 24 degree compression ramp model

2.1 Laser Schlieren System

Figure 2 shows the schematic of the Laser Schlieren set-up used and the experimental procedure followed for flow field analysis in each case. A parallel sheet(in Y-Z plane) of low powered(15 W) diode laser with provision for manual vertical(Y-direction) and motorized horizontal(X-direction) (both with an accuracy of ±0.01 mm) is passed through the test section and received by an array of very high response(4 ns) photodiodes placed on the opposite side of the test section. Each photodiode has an active area of 0.66 mm^2 and arranged on a 1 mm pitch in common cathode configuration. The laser sheet therefore traverses approximately 10 boundary-layer thicknesses at each survey position.

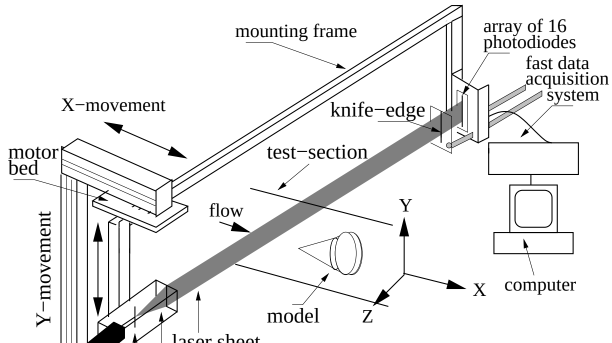


Fig. 2: Schematic of the Laser Schlieren setup

The principle of operation of a Laser Schlieren system is the same as that of an ordinary Schlieren system except that in this voltage signals are obtained in accordance with the density gradient fluctuations in the flow field, see figure 3. When the laser sheet touches an oscillatory shock, the diffracted light appears periodically, and a time trace obtained from the array of 16 photodiodes shows unsteady voltage signals. The arrangement gives an idea of the existing density gradient fluctuations in the flow and hence, an insight to the fluctuating nature of flow. This arrangement is free from structural vibrations as it is mounted on a table completely isolated from the wind-tunnel. It may be further pointed out that the tunnel wall boundary-layer equally influences each photodiode measurement, irrespective of its position in freestream/interactive field, in each case as shown in figure 1. The arrangement allows the interactive flow field to be scanned both perpendicular to the freestream direction and parallel to the model test surface. In both perpendicular and parallel mode, the complete array was kept 0.6±2% mm above the model surface. This, however, initially required very careful alignment of the laser sheet itself. All the data were sampled at 5 kHz. The instrument, however, was not calibrated against a known density gradient.

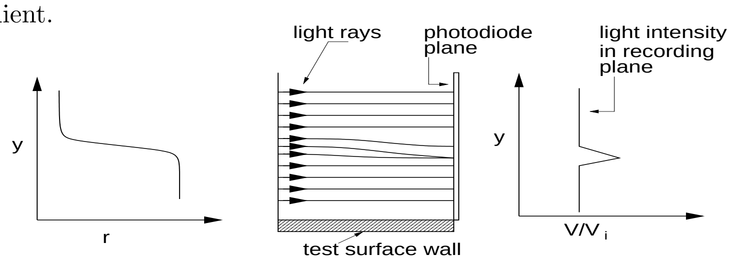


Fig. 3 Representation of density gradient profile across a shock wave

3. RESULTS AND DISCUSSIONS

3.1 Fluctuating Density Gradient Field

Figure 4a shows the fluctuating density gradient profiles at cone-flare junction of HAC model with the photodiode array perpendicular to the freestream direction. Here the voltage signal, V (mV), for each channel is non-dimensionalised by its initial value, V_i (mV), during the beginning of the flow. And since the knife-edge was placed in the direction of the flow, a decrease in voltage followed by an increase represents a density gradient. The time-dependent profiles show a strong inflection point away from the model surface representing the main shock that exhibits an up and down motion in the Y-direction.

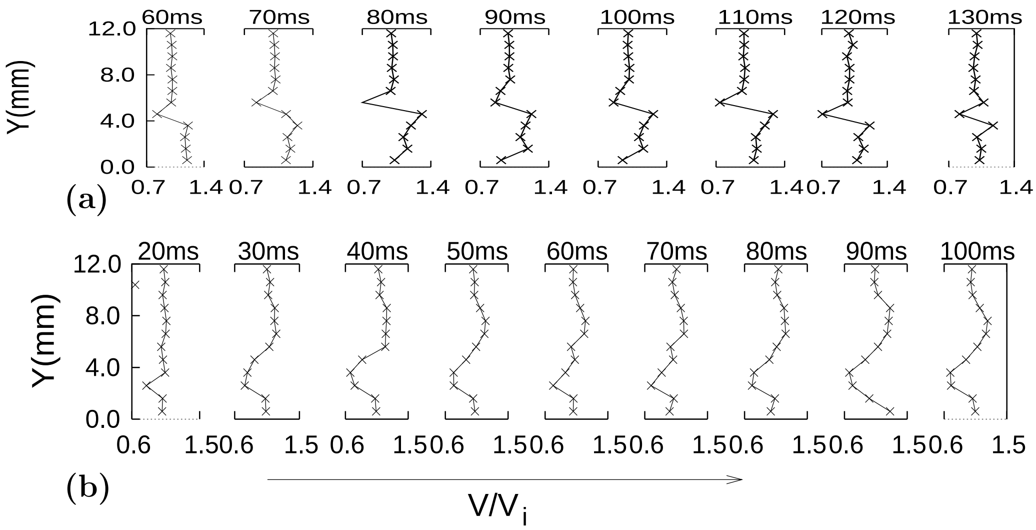


Fig. 4: Time-dependent density gradient profiles
(a) Halis Axisymmetric Configuration(HAC) model, X/L=0.80
(b) 24 degree compression ramp model, X/L=0.560

This suggests that as the separation bubble expands and contracts during its lifetime it displaces the main shock vertically in accordance with change in its size thereby influencing the entire flow field above the interaction region. Away from the main shock the profiles show absence of any density gradient thereby representing the freestream flow conditions. Figure 4b shows the density gradient profiles in the separated region of ramp model. Here the inflection point represents the separated shear layer since the interaction region in this case is much larger than that on HAC model due to the considerable variation in model size, figure 1. It can be seen that here the shear layer also exhibits an up and down oscillatory motion over a period of time. It can, therefore be seen that it is possible to capture the oscillatory nature of the separation bubble and separation shock in each test case.

3.2 Signal Analysis

Figure 5 shows the simultaneously sampled time histories from the photodiode signals in the vicinity of separation location on HAC model wherever the voltage signals from neighboring channels were found to exhibit mirror-imaging. The vertical distance (Y), where such a behavior was exhibited, varies depending upon the location where the flow field was scanned in the separation region. Figure 5a shows the case near separation and figure 5b in the separated region with the photodiode array perpendicular to the freestream direction. These scanning locations were chosen in accordance with schlieren pictures taken earlier with a scale mounted on the test-section window. One low-frequency oscillation can be observed from these plots. However, they are out of phase at different axial locations. The reason for this being that figure 5a shows the density gradient signals from an oscillating separation shock while that in figure 5b are from a fluctuating separated shear layer that responds in accordance with the movement of separation shock. The signals from the neighboring photodiode channels therefore show that when the separation bubble expands and contracts during its lifetime, the separation shock and separated shear layer follow opposite motions, i.e., when the separation shock moves forward, the separation bubble contracts and $vice-versa$. The mirror-imaging of signals from neighboring channels was also observed for the tests with the compression ramp flow (Verma and Koppenwallner, 2000).

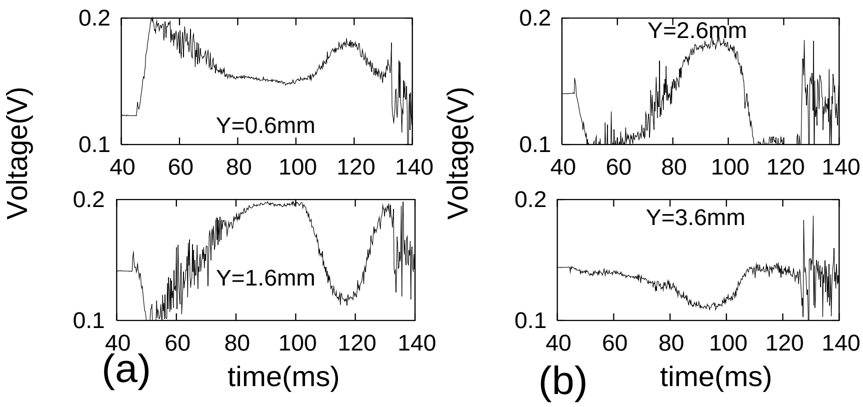


Fig. 5: Simultaneous time traces of voltage signals(close to surface) near the separation region on the HAC model (photodiode array perpendicular to the freestream direction)
(a) X/L=0.66
(b) X/L=0.74

It can be further inferred from these plots that the mirror-imaging effect is only exhibited by the low-frequency fluctuations and not by the high-frequency changes indicating, as is known, that separation is associated with low frequency oscillations. These observations help to determine that the random movement of separation shock and the associated mean pressure distributions are the physical mechanisms responsible for high levels of unsteady loads near separation locations (and hence, reattachment locations). Once this is known, a question arises: what causes the separation shock to oscillate ? The most convincing theory is that of Maull (Maull,1969) which is based on the imbalance of mass of fluid reversed at the reattachment point to that scavenged from the separated region resulting in an unsteady mass exchange. Charwat et al. (1961), while studying heat transfer effects in separated flows also observed that the model of mass exchange appeared to yield more accurate semi-empirical correlations of measurements.

3.3 Cross-correlation Functions

Figure 6 shows the space-time correlation for the HAC model, as a function of time delay, between the voltage signals from photodiode channels say A and B, and locations B and C in the vicinity of separation location. These channels are chosen wherever mirror imaging of the voltage signals is observed between adjacent photodiodes, as was shown in figure 5. The point of interest is the value of the correlation at approximately zero time delay. It can be seen that the space-time correlation value between these locations show opposite trends. Locations A and B(which are in close proximity to one another) show a large negative value while B and C show a relatively large positive value indicating that when photodiode A experiences a rise in density(as across a shock), the photodiode B experiences a fall. Locations B and C experience a similar rise and fall of density.

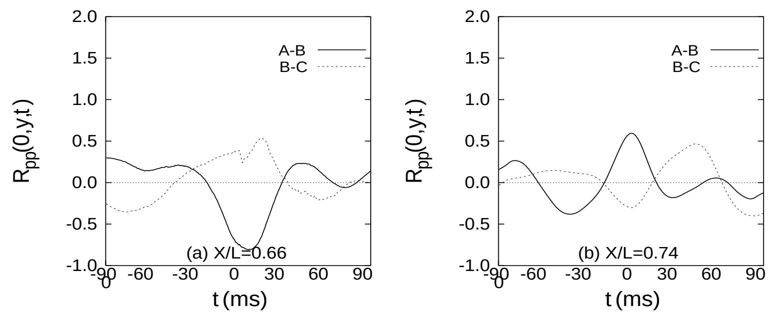


Fig. 6: Space-time correlation functions near the oscillating separation shock locations (photodiode array perpendicular to the freestream direction); HAC model

Figure 7 shows the space-time correlations obtained at separation location for the ramp model with photodiode array parallel to model surface. Here the procedure followed is similar to that followed in literature for intermittent pressure signal on ramp flows and not as previously described for figure 6. It can be seen that the peak value of R_{pp}, see figure 7a, at the start of interaction is about 0.75 which is lower than the value of R_{pp} in the undisturbed boundary layer, where the corresponding value is about 0.98(shown by a solid curve). As further distance is progressed, the peak value shows a jump with a significant increase in value(up to approx. 0.85). It has been suggested by Andreopoulos et al.(1988) and Garg and Settles (1996) that such a behavior of cross-correlation curves corresponds to the mean location of separation shock where the oscillatory behavior of the shock wave is believed to contribute to the jump in R_{pp}. In the separation region, therefore, the flow is dominated by large-scale oscillating motions while inside the separated region the correlations get even more complicated, figure 7b. Here the density field is effected by structures moving in the direction of the external flow and also by those structures close to the wall moving in the opposite direction in addition to any residual effects of shock oscillation.

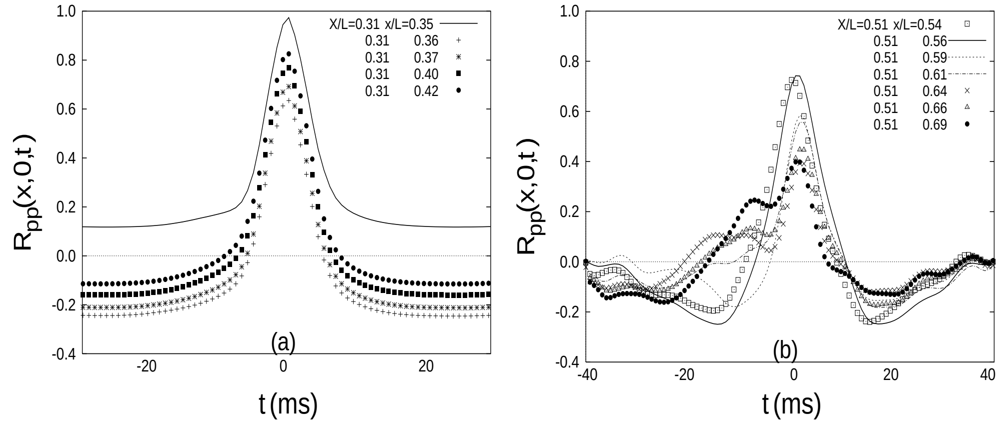


Fig. 7: Space-time correlation functions for photodiode locations (close to surface) near the oscillating separation shock; compression ramp model (photodiode array parallel to model flat surface)

(a) at the separation region

(b) inside separated region

Some interesting features are seen to develop in the cross-correlation functions for separated flow, figure 7b. Initially the cross-correlation shows a peak at zero time delay which shifts to positive τ with increase in photodiode spacing. Correlations further downstream show the peak value at positive τ to decrease with a subsequent development of a peak at negative τ that tends to increase for large photodiode spacings(ξ=0.64, 0.66, 0.69). The appearance of maxima in R_{pp} at both positive and negative time delay corresponds to the separated shear layer eddies moving downstream and the backflow adjacent to the wall, respectively (Dolling(1990)). Though the peak in R_{pp} occurred at same positive τ with increasing photodiode separation distance, ξ, the peak at negative time delay was seen to shift from a larger time delay to a smaller one. This seems to indicate that as we move further into the separated region increasing reverse velocities are encountered along with convective velocities. These results are consistent with the results from previous studies that use pressure transducers to obtain surface pressure signals in order to study the interaction region of such flow situations. This helps to validate the use of this simple technique to study the basic characteristics of such flows in complex flow geometries since it uses only a small laser and an array of photodiodes that can be moved to scan any section of the flow field of interest.

These observations are consistent with the view that the separation shock translates back and forth in the vicinity of the separation point on the model surface, in accordance with the expansion and contraction motion of separation bubble. This oscillatory nature has been known for quite sometime now to be responsible for high levels of fluctuating pressure loads.

3.4 Power Spectra

Power spectral density estimates provide additional support for the above findings. Figure 8 shows the power spectral density plots for the voltage signals obtained from the inflection points of interest, as seen in the density gradient profile for different axial locations on a HAC model. Here G(f) (mV^2/Hz) is the power level plotted against the frequency, f (kHz) on a linear-linear scale. It can be very clearly seen that the large amplitude, high energy fluctuations (i.e., those caused by the shock wave) fall in a fairly narrow low frequency range. Away from the interactive field, location (c), the spectrums are seen to relax showing undisturbed flow conditions in the freestream. Near reattachment location, figure 8ii), a significant increase in energy of both low and high frequency fluctuations is observed relative to that at cone-flare junction, figure 8i), which is primarily due to the random fluctuation of instantaneous position of reattachment shock and the reattaching shear layer.

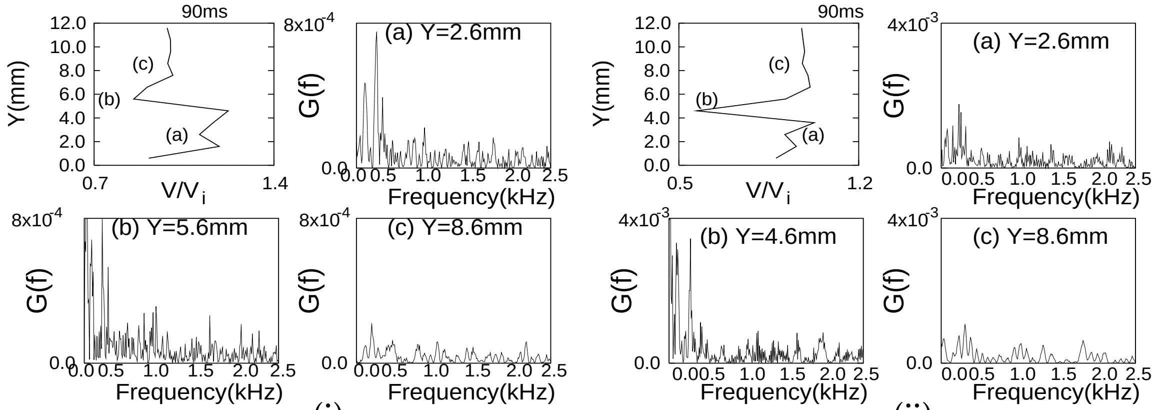


Fig. 8: Power spectral density plots of voltage signals obtained for inflection point locations on the density gradient profiles as indicated
(i) X/L=0.800 (cone-flare junction)
(ii) X/L=0.900 (ahead of reattachment region)

4. SUMMARY

A simple laser schlieren technique has been used to study the off-surface flow field characteristics related to shock-wave/boundary-layer interaction near the separation region of a HAC and a 24^o compression ramp model. An extensive data set obtained from simultaneous multichannel recordings of the fluctuating density gradients helped reveal the unsteady aspect of the interaction in each case.

Time-dependent density gradient profiles show an up and down oscillatory motion of the separation bubble. Space-time correlations in the vicinity of separation indicate the separation shock to be unsteady that translates back and forth in the vicinity of the separation point on the model surface, in accordance with the expansion and contraction motion of separation bubble. Further, the flow is found to be affected by two basically different phenomena, namely, the up and down motion of separation shock wave and convective flow structures, the relative importance of each being strongly dependent on the location within the interaction. The observed results are in conformity with previous studies made from surface pressure signals. Due to its simplicity and accessibility, this technique can be used to study unsteady flow on complex flow geometries and to obtain a point by point analysis of the interactive flow field.

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