HIGH TEMPERATURE SKIN FRICTION MEASUREMENT
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ABSTRACT
Skin friction measurements are critical to the design of aerodynamic and propulsive systems encountered in the hypersonic flight regime. Mechanical, force balance type skin friction sensors have been in use at Langley Research Center for many years, however, hostile environments have generally been avoided. Tests in the hypersonic propulsion facility began in early January 1989, where the expected parameters were estimated as follows: Q - 1000 to 4000 psf; C_f - 0.002 to 0.004; wall temperature - 2000°F approximately; Q - 50 to 200 Btu/ft^2/sec; static pressure - less than 3 atmospheres; SPL - 130 db approximately and peak acceleration of 25 g's.

The sensor configuration, for use in this experiment, utilized an existing balance, modified to provide thermal isolation and an increased standoff distance. Test run times were on the order of 20 seconds with ambient air then used to cool the test section and the balance. Under these conditions, the modified balance performed satisfactorily. A preliminary test in which the balance was subjected to the acoustic and structural vibration environment was completed and the balance performed satisfactorily. The balance is an inertially balanced, closed loop servo system where the current to a moving coil motor needed to restore or null the output from the position sensor is a measure of the force or skin friction tending to displace the moving element. The accuracy of the sensor is directly affected by the position sensor in the feedback loop which, in the present device, is a linear variable differential transformer which has proven to be influenced by temperature gradients. As a result, new position measurement schemes are being investigated. Some experimental results will be discussed in the paper.

INTRODUCTION
Skin friction or wall shear measurements are required in the development of hypersonic vehicles, particularly in propulsion system design, to resolve combustion efficiencies, resolve film cooling effectiveness and to resolve uncertainties in combustor models used in full scale flight predictions.

Mechanical, force balance type skin friction sensors have been developed at Langley Research Center for the last two decades [1], [2], [3]. The basic design takes the form of a parallel linkage configuration in order to overcome most of the disadvantages inherent in the inverted pendulum configuration [3]. It should be emphasized that the LaRC design is rugged and it is inertially balanced.

Various LaRC designs have been used to make direct skin friction measurements in flight, moderately hot (300°F) and cryogenic environments. However, tests in more hostile environments have not been conducted.

The test parameters, to be encountered in LaRC's hypersonic propulsion facilities, were quantified as follows:

C_f = 0.002 to 0.004
Q = 1000 to 4000 psf
T_w = 1000°F approximately
Q = 50 to 200 Btu/ft^2/sec
SP - less than 3 atmospheres
SPL = 130 db approximately
a_pk - approximately 25 g's

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BALANCE DESCRIPTION

The high temperature balance is a modified form of a flight balance reported earlier. Functionally, the new balance is identical to the previous unit with the exception that thermal insulation has been added to the new unit. A brief description of the balance is provided as follows.

The balance, shown in Figure 1, is a type one servomechanism with both mechanical and electrical components. As shown, a parallel-link mechanism is fastened to the outer cage of the balance through a stationary plate via three flexure pivots. This mechanism has two moving plates. The sensing element and the armature of the position sensor are installed on the upper moving plate while the coil windings of the force motor are installed on the lower moving plate. The permanent magnet of the motor and the position sensor are mounted on the stationary plate.

The motor is used to exert a restoring force on the lower plate when a skin friction force is experienced on the sensing element. The position sensor, a linear variable differential transformer (LVDT), is used to measure the movement of the sensing element. The output from the LVDT provides not only the error signal but also indirectly the damping required by the servomechanism.

With the short run time (on the order of 20 to 30 seconds) as a condition, it was decided to utilize an existing skin friction sensor, but to increase the sensing element standoff distance with a thermal insulator to isolate the balance interior from the severe tunnel conditions. A thermocouple to monitor the interior temperature of the balance was installed near the stationary plate inside the balance.

Several photographs are included. Figure 2 shows the disassembled balance with the cylindrical sensing element mounted to a boron nitride insulating standoff as well as the boron nitride mounting case, both intended to minimize the heat conductance to the internal balance components. Also observe that the cylindrical sensing element is made of the same material and thickness as the tunnel wall in order to avoid a thermal hot spot. This presented a perceived geometrical problem which will be discussed later. Figure 3 is a front view of the assembled balance.

Due to the high temperatures involved, the seal between the wind tunnel wall and the balance adapter was a .015" flat soft copper gasket. An identical gasket was used to seal between the boron nitride case and the balance adapter.

The cylindrical sensing element is one-inch in diameter and the gap between the sensing element and the housing is 0.010 inch. The full scale force range of the balance is adjustable from 20 gm to 40 gm, corresponding to shear stresses of 3.95 gm/cm and 7.89 gm/cm, respectively. The output full scale voltage is 10 volts DC and the overall precision is better than 0.5% of full scale.

TEST FACILITY

The high temperature skin friction balance was tested in the Test Cell Number Two of the Combustion-heated Direct Connect Test Facility at LaRC. A line sketch and a photograph of the rectangular test duct are shown in Figures 4 & 5, respectively. Note that the balance is mounted on the side wall near the exit of the duct. Note also the ramp-shaped fuel injectors shown in Figure 4. These injectors provide the horizontal injection of hydrogen fuel and may be the source of shock waves introduced in the duct. Figure 6 shows a close-up view of balance. Note the sudden enlargement of the duct just downstream of the balance.

TEST RESULTS

Because of the severe vibration and acoustic environment, the susceptibility of the balance to these inputs was investigated by mounting a unit to the tunnel wall with no penetration to the tunnel interior and several tunnel runs conducted. The balance output revealed no observable effects from these interferences.

Because of the short run time, it was decided that the balance may not require active cooling and thermocouple readouts verified that natural cooling by ambient air was sufficient.

The balance was tested on four different days, with six to seven 20 second runs per day. The total temperature of the flow usually exceeded 1500'F. Several records from a sample test are included in the following. Figures 7 & 8 show three time
histories of pressure distribution along the duct top and bottom wall, respectively. The pressures shown are normalized against the static pressure at the nozzle exit, which is approximately equal to the atmospheric pressure. The cycle 10 trace, shown in diamond symbols, is the pressure before combustion is initiated. The cycle 22 trace, shown in open squares, represents the pressure after the full combustion is established. The balance location are superimposed in these figures in an effort to emphasize that the static pressure is only few psi less than atmospheric and that pressure gradient might also exist at this location.

Balance temperature history for five consecutive runs spanning over 66 minutes are shown in Figure 9. Finally, a recording of the balance output is included in Figure 10.

The temperature traces shown in Figure 9 clearly indicated that the temperature within the balance remained essentially unchanged during any one of the 20 second runs. The nearly constant temperature condition is significant since the output of the displacement sensor was known to drift with temperature and was a major source of concern before the test. This means that the balance output could be nulled by taking the wind-off zero before each run. Note that Figure 9 also indicates that the balance finally reached 115°F after five consecutive runs. This means that thermal insulation as well as natural cooling by ambient air are sufficient for this application.

Two observations, regarding performance of the balance, were made from the very beginning. First, the balance always returned to zero after each run, indicating that the balance was functional and was not affected by the high temperature environment. Second, large negative force readings were registered as shown in Figure 10.

Initially, it was suspected that the negative force reading was caused either by the reverse flow in the duct, by misalignment, or by leakage between the balance and the outside. Because of uneven discoloration of the sensing element, it was initially thought that a slight misalignment at the surface caused a shock to form on the downstream edge of the cylindrically shaped sensing element causing the pressure, acting in the gap, to force the element in the negative flow direction. To eliminate or minimize this condition, a new sensing element was installed which had a much smaller diameter behind the surface with a beveled transition to the same surface diameter as previous. This configuration is shown in Figure 1. Subsequent testing revealed that negative flow directions were encountered with this configuration also. Disassembly of the balance after the first set of runs revealed foreign particles between the boron nitride case and the copper seal, indicating a possible flow of gas between the two. An attempt to seal the balance with RTV sealing compound (a high temperature version) for the second set of runs was not successful. The balance was leak checked and a leak was detected at the boron nitride case to adapter seal. The leakage was also verified by orienting the balance for the next series of runs with its sensitive axis perpendicular to the flow direction. A more thorough leak check was performed after the last run where it was found that at least a 10 psi pressure differential, between the back chamber and the exterior, was required to generate the amount of negative force reading seen during the test. This seemed to be much more severe than could have occurred in any test because the pressure differential across the duct wall at the station where the balance is located was never more than 5 psi (see Figures 7 or 8). Therefore, it was decided that the negative force reading of the balance was indeed partially caused by a reverse flow at that location. The presence of the reverse flow, however, was not verified by any other independent means.

The balance was disassembled again. At this time several deep cracks were noted in the boron nitride material. The cause of this fracture is unknown.

CONCLUSIONS

While the attempt to obtain high temperature skin friction force data using the modified balance described herein was not conclusive, several positive results were gained which could aid in the future development program.

The test proved that the basic configuration and design of the mechanical balance is satisfactory. Different gasket material will be used to provide better...
sealing. Other types of thermal insulation or a metal standoff, with active cooling, will be tried. Development of other types of mechanical or electro-mechanical sensors in making direct skin friction measurements is being pursued. This includes the use of alternate displacement sensors and the applications of other transduction principles in an effort to reduce the physical size of the instrument. It is planned to fabricate a new test duct to accommodate additional axial test locations, in order to study the reverse flow phenomena.

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NOTE: Dimensions are in inches.

Figure 1 Mechanical Schematic of Balance
Figure 7  Duct Top Wall Pressure Distribution

Figure 8  Duct Bottom Wall Pressure Distribution
Figure 9  Typical Balance Temperature History

Figure 10  Typical Balance Force Output
DESIGN AND FABRICATION OF AN INTEGRATED HOLOGRAPHIC LASER-DOPPLER OPTICS

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ABSTRACT: In this paper we present two integrated holographic Laser-Doppler optics. The first one is designed to measure one component of the velocity field of a fluid. Three such LDV optics may be used for the measurement of the three velocity components. The second type serves for the measurement of the velocity gradients and of the velocity correlations.

1. INTRODUCTION

Holographic Optical Elements (HOEs) are well suited for use with monochromatic laser sources. The HOEs offer the following advantages over conventional optics:
(i) Once the master HOE is fabricated, its replication is cheap.
(ii) Since a HOE is stored in a thin film (approximately 10μm thick) on a substrate, it is lightweight and occupies only a small volume.
(iii) A HOE can perform different functions. For example, it can act as a lens and a beamsplitter at the same time.
(iv) Different HOEs can be recorded in the same area of a holographic layer. This allows the simultaneous existence of several lenses, i.e. a multifocus lens.
(v) The position of the focus of a holographic lens is not restricted to the optical axis. Thus, off-axis lenses can be fabricated, which focus the incident wave to a point away from the optical axis.
(vi) Several off-axis lenses can be joint together so that their foci coincide in one point. This lens array is equivalent to a large aperture lens. For example, such a lens array can be used in LDV measurements to collect the light scattered by the particles in the fluid.

In this paper we present two types of miniaturized Laser-Doppler optics composed of HOEs. The first type consists of a holographic beamsplitter, two holographic lenses, which focus the laser light to the detection volume, and a holographic lens, which collects the scattered light. These components are integrated into a compact optical system. The operation wavelength is 514 nm. The laser light is guided from the laser source to the LDV optics with the help of a polarization preserving monomode fiber. The collecting lens focuses the signal wave scattered by the particles onto the face of a light cable, which transports the signal to the electronics.

The second miniaturized holographic Laser-Doppler optics produces two detection volumes close to each other. The distance between these volumes is of variable length. With this optics we measured the gradients of the velocity field in a swirling flow.

2. BASIC PRINCIPLES OF VOLUME HOLOGRAPHY

A volume phase hologram /1/ is a piece of a transparent dielectric whose refractive index varies continuously in space. The fabrication of a volume phase hologram in dichromated gelatin (DCG) involves three main steps /2/:
(i) Deposition of the gelatin layer on a glass substrate and sensibilisation of this layer with ammonium dichromate.
(ii) Exposure of the holographic layer to the interference pattern formed by the reference and the object wave.
(iii) Development and post processing of the exposed gelatin layer.

The simplest holographic structure that can be recorded in the DCG layer is a grating of the transmissive type. During the exposure the in
terference pattern of two plane waves, which constitute the reference and the object waves, is recorded throughout the gelatin layer. The intensity distribution is given by

\[ I = I_0 (1 + m \cos(K \cdot r)) \]  

(1)

In the formula \( I_0 \) is the mean intensity, \( m \) the amplitude of modulation and \( r = (x, y, z) \). The vector \( K \) is called the grating vector. The planes of constant intensity are perpendicular to \( K \). The grating period is given by \( \Lambda = 2\pi/K \). After the exposure the gelatin layer is developed. The development converts the recorded intensity distribution into a variation of the refractive index of the layer. In general the conversion is non-linear, but it conserves the periodicity of the intensity distribution.

The resulting refractive index variation diffracts the incident light wave during the reconstruction. In contrast to thin gratings, where the incident wave generates many diffracted orders, volume gratings diffract the incident power predominantly in one order. Hence, illuminating the holographic volume grating with a plane wave front similar to that of the reference wave will generate the plane object wave (see Fig. 1).

The efficiency of the conversion of the reconstruction wave into the signal wave is measured by the diffraction efficiency, i.e. the ratio of the diffracted power to the incident power. Theoretically the diffraction efficiency of the volume grating can be as high as 100\%. If the diffraction efficiency of the grating is 50\%, it acts as a beamsplitter.

Holographic volume gratings exhibit wavelength and angular selectivity, i.e. the hologram diffracts the reconstruction wave only over a small range of wavelengths and angles of incidence. The central wavelength \( \lambda \) and the angle of incidence \( \theta \) in the hologram are related by the Bragg-condition

\[ \cos(\Phi - \theta) = \frac{\lambda}{2n_0 \Lambda} \]  

(2)

where \( n_0 \) is the mean refractive index and \( \Phi \) is the slant angle, i.e. the angle between the grating vector and the hologram normal. The bandwidth and the width of the angular range decrease monotonically with the thickness of the gelatin layer.

A holographic lens is recorded with a plane or a spherical reference wave and a spherical object wave. Locally the lens can be considered as a volume grating, if its f-number is not too small. Thus, the holographic lens exhibits locally the same
properties as the volume grating. The recording and the reconstruction of an off-axis holographic lens is depicted in Fig. 2. The reference wave is a plane wave and the object wave is a divergent spherical wave. If the reconstruction wave propagates in the direction opposite to the original reference wave, the conjugate of the object wave, i.e. a convergent spherical wave, will be generated.

3. DESCRIPTION OF THE INTEGRATED HOLOGRAPHIC LASER-DOPPLER OPTICS

In a dual beam LDV system the incident laser beam is first split into two beams of equal intensity. The beams are then focused onto the detection volume, where a particle following the flow scatters the laser light. A lens collects the scattered light, which contains the information about the velocity of the flow in form of frequency shift relative to the incident laser beam. The signal is then analyzed electronically.

From this description of the operation of a dual beam LDV system follows that the integrated holographic LDV optics contains a beamsplitter, two lenses to focus the beams onto the detection volume and a lens to collect the scattered light. All components can be integrated into a compact LDV optics, if the distance between the detection volume and the LDV optics remains fixed.

Fig. 3 depicts the operation mode of the miniaturized holographic LDV optics. The main body is formed as a rectangular prism. The hypotenuse of the triangular projection shown in Fig. 3 is 61 mm long, the other two sides have a length of 44 mm. The holograms H1, H2, H3 and the main body are pasted together.

The laser light (514 nm) enters the HOE optics through a polarization preserving monomode fiber (PMMF). A holographic beam splitter H1 splits the incident beam into two beams of equal intensity. The two holographic lenses H2 focus the two beams towards the detection volume M. The distance between the two lenses is 35 mm. The detection volume is located 80 mm from the front surface. The intersection angle between the two beams,
which form the detection volume, is 25° corresponding to a fringe period of 1.2 μm.

The light scattered by a particle towards the LDV optics is collected by the holographic lens H3 fixed above the hologram H2. Its aperture is elliptic with the long diameter equal to 35 mm. The scattered light is focussed onto the front face of a light cable, which transports the signal to the photomultiplier.

The beamsplitter hologram is a symmetric grating of the transmissive type. Fig. 4 gives the diffraction efficiency η, the transmittance T and the energy balance \( \Sigma = \eta + T \) as a function of the deviation from the Bragg-angle \( \alpha \) in air. At Bragg-incidence \((\alpha = 0°)\) the diffraction efficiency and the transmission are equal to 42% in air, corresponding to 46% with respect to the gelatin layer. There is a loss of light power of 8% due to scattering and absorption in the hologram.

The angular sensitivity in air, i.e. the diffraction efficiency as a function of the angle of incidence, of one of the holographic lenses H2 is depicted in Fig. 5. The efficiency at Bragg-incidence is 82% in air (90% in the gelatin layer).

Using the data of Fig. 4 and Fig. 5 one calculates an overall efficiency of 83% of the optical system composed of the beamsplitter and the two lenses with respect to the gelatin layer. In practice this value can be achieved with appropriate anti-reflection coatings. Otherwise each gelatin-air interface reduces the overall efficiency by approximately 4%.

The collecting lens has a mean efficiency of 66% in air (74% with respect to the layer). The diffraction efficiency varies over the aperture between 58% and 75% with the maximum at the midpoint and the minimum at the edges. This variation in efficiency is caused by the large variation of the local grating period of the lens. The development process of the holographic layer can be optimized to give high diffraction efficiency (>90%) only for a small range of grating periods.

The handling of the miniaturized holographic LDV optics is very simple. There is no adjustment of the various optical components, because they are pasted together in a fixed geometry. The light is launched into the system and extracted from it with optical waveguides. Moreover, the system occupies only a small volume and is lightweight.

Fig. 6 depicts a velocity profile measured with the holographic LDV optics. The data represent the axial velocity of the fluid (limonene) as a function of radial position across the diameter of a vortex generator apparatus as described by Sarpkaya.151. The data were taken with a vane angle equal to 0°. In this configuration the flow exhibits no swirl and is turbulent.

FIG. 4: Diffraction efficiency η, transmittance T and energy balance \( \Sigma = \eta + T \) of the holographic beamsplitter as a function of the angle of incidence \( \alpha \).

FIG. 5: Angular sensitivity of one of the holographic lenses H2.
4. MINIATURIZED HOLOGRAPHIC OPTICS FOR THE MEASUREMENT OF THE GRADIENTS OF A VELOCITY FIELD

In the foregoing paragraph an integrated holographic LDV optics for the measurement of one component of a velocity field was described. In this chapter we present a miniaturized holographic optics, which produces two detection volumes. With the help of this holographic system we measured the velocity gradients in the vortex bubble of a swirling flow.

Fig. 7 gives a sketch of the operation mode of the holographic optics /3/. The system consists mainly of two holographic lenses H1 and H2. The lens H1 produces the detection volume M1 and the lens H2 produces the volume M2. Each lens has a diffraction efficiency of 50% for the following reason: Consider the upper laser beam incident on H1. The lens H1 diffracts this beam with an efficiency of 50% towards the detection volume M1. The transmitted power is then diffracted by the lens H2 into the detection volume M2. Because the two volumes M1 and M2 are close together, the beams from H1 to M1 and from H2 to M2 are nearly parallel. Thus, if the lens H2 would have a diffraction efficiency of 100%, it would diffract the beam from H1 to M1 completely. Consequently, the detection volume M1 would not be formed. Reducing the diffraction efficiency of H2 to 50% allows for the formation of the detection volume M1. In this way each detection volume contains 25% of the incident power.

The laser power is launched into the holographic system via two polarization preserving monomode fibers (PMMF). The light leaving each fiber is contained in both detection volumes. With the help of an acusto-optic cell the frequency of the laser light, which is guided by one of the fibers, is shifted in frequency. By means of this it is possible to determine the direction of the velocity gradient. If the direction of the velocity vector is of no interest, the two fibers can be replaced by one fiber and a holographic beamsplitter as in the case of the integrated LDV optics.

The geometrical data of the holographic optics are:
(i) Dimensions: 100 mm x 200 mm x 140 mm.
(ii) Distance between the detection volumes and the front surface: approximately 24 mm.
(iii) Intersection angles between the beams forming the detection volumes: 7° and 9°.

The distance between the detection volumes M1 and M2 can be varied. Thus, it is possible to measure the spatial correlation function of the velocity field.

As with the integrated LDV optics the handling of the system is very easy. The only adjustment necessary to use the optics is to place the detection volumes to the desired sites with the help of two micrometer skrews and to install the receiving optics.
5. DEMONSTRATION OF THE FEASIBILITY OF THE HOLOGRAPHIC LDV OPTICS

To demonstrate the feasibility of the holographic LDV optics, we present data of the axial velocity and of the radial component of the gradient of the axial velocity measured in the bubble structure of a vortex breakdown [4]. The vortex was generated in a conical tube apparatus similar to that used by Sarpkaya [5]. The swirl was produced by means of a radial inflow of the fluid through a set of vanes in a cylindrical tube with a conical test section. Under appropriate conditions the bubble-like structure of the vortex breakdown occurs.

The fluid used in these experiments was limonene. This liquid has nearly the same kinematic viscosity as water. Its refractive index (1.48) coincides with that of the glass, which was used to fabricate the tube. In this way we were able to suppress the wave front distortion of the laser beam at the interface between the cylindrical tube and the liquid.

Fig. 8 presents the axial velocity as a function of the position across the tube diameter. Curve 1 gives the velocity profile in the approach section upstream of the vortex bubble; curve 2 was measured in the bubble and curve 3 at the tail of the bubble. The measurement shows clearly the retardation and the reversal of the axial flow.

The radial component of the gradient of the axial velocity in the vortex bubble is depicted in Fig. 9.

For more information on the structure of the vortex bubble and a detailed discussion of the results the reader is referred to Ref. 4.

6. CONCLUSION

In this report we discuss the properties of two types of integrated holographic LDV optics. They were used for the experimental determination of the velocity, of the velocity gradient and of the spatial correlation of the velocity field. All devices are composed of high efficiency HOE that facilitate low light level measurements and ensure high spatial resolution. The optical characteristics of the specific HOEs and of the integrated holographic optics were experimentally determined and evaluated. Of particular interest are the small size and weight of the
holographic devices compared to the weight and size of the bulky glass components usually utilized in the fabrication of LDV optics. Hence, the holographic optics may be positioned at strategic locations in the simulation facility.

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