

Fluid-Thermal-Structural Interactions in Ramp-Induced Shock-Wave/Boundary-Layer Interactions at Mach 6

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Experiments were conducted to study the fluid-thermal-structural interactions of a compliant panel exposed to ramp-induced shock-wave/boundary-layer interactions (SWBLIs) at Mach 6 for laminar and transitional incoming boundary-layers. For some cases, boundary-layer trips were introduced to generate a turbulent boundary layer over half of the interrogation area. Infrared thermography was used to measure the variations in surface temperature on a compliant panel embedded in a rigid ramp. A plenum box was designed to enable the control of the back pressure behind the compliant panel. High-frequency pressure transducers measured the mean and fluctuating static pressure inside the cavity. Simultaneous temperature and pressure measurements enabled the analysis of the thermal and vibratory response of the compliant panel when subjected to SWBLIs for multiple ramp angles. The thermography also revealed an unexpected low temperature region visible on the panel at high ramp angles and Reynolds Numbers. A spanwise-nonuniform boundary layer generated by upstream trips resulted in the excitation of different modes on the panel. A study on the effects of the pressure difference on the panel natural frequencies revealed that the modes are diversely affected at low pressure differentials.

Nomenclature

f	=	frequency
M	=	Mach number
p	=	pressure
Δp	=	static pressure differential across panel
Re	=	unit Reynolds number
t	=	time from acquisition trigger
T	=	temperature
δT	=	temperature difference with respect to initial temperature
ΔT	=	temperature difference of panel with respect to the support
y	=	height from surface of flat plate

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I. Introduction

SHOCK-wave/boundary-layer interactions (SWBLIs) pose unique challenges for the slender airframes and sharp control surfaces characteristic of high-speed airbreathing aircraft. Spikes in mean pressure and thermal loading have been shown to occur in SWBLI regions; thus, predicting the location and behavior of such proves critical for assuring aircraft structural integrity and fatigue resilience [1]. SWBLIs frequently lead to turbulent boundary-layer separation and corresponding unsteady motions spanning a wide range of frequencies [2]. Low-frequency motion has been shown to be capable of coupling with compliant structures [3]. Turbulent boundary layers thus present a particular danger for geometries such as control surfaces where SWBLIs are present and thin, lightweight structures are used to reduce aircraft weight.

Previous studies have shown that the thermal loading on a compliant panel in a ramp-induced SWBLI may have a significant impact on the panel vibrations [4]. A multitude of studies have investigated the heating on rigid structures [5], but a characterization of the heating effects on compliant structures is necessary to fully understand the fluid-thermal-structural interactions (FTSI) occurring in ramp-induced SWBLIs. The present study uses infrared thermography and high-frequency Kulite™ pressure transducers to examine the heating loads and unsteady pressure variations on rigid and compliant ramps at various angles and flow conditions at Mach 6.

II. Experiments

A. Facility

The tests were conducted in the NASA Langley Aerothermodynamics Laboratory 20-Inch Mach 6 blow-down wind tunnel [6]. The facility uses dried, heated, and filtered air and is capable of 20 minute run times, although each experiment in the present campaign lasted approximately 10 seconds to allow for multiple runs per day. The nominal reservoir conditions are stagnation pressures of 0.21-3.3 MPa with stagnation temperatures of 422-556 K, producing flows corresponding to unit Reynolds numbers of $1.6\text{-}24 \times 10^6 \text{ m}^{-1}$ [7]. The test section measures 520.7 mm by 508 mm and has 6 windows for optical access. For these experiments, the top, front optical access point was fitted with a special Zinc Selenide (ZnSe) antireflective-coated window to allow for infrared (IR) thermography imaging. The tunnel was operated at two unit Reynolds number conditions (Table 1) to examine the interactions of both transitional and turbulent boundary-layers with ramp-induced shocks: $6.6 \times 10^6 \text{ m}^{-1}$ and $23.6 \times 10^6 \text{ m}^{-1}$ were chosen based on a transition study of this model and facility by Kegerise et al. [7].

Table 1 Run Conditions

Condition	Trips	M_∞	Re_∞ (10^6 1/m)	P_0 (MPa)	T_0 (K)
A1	Off	5.96	6.6	0.86	505
A2	On	5.96	6.6	0.86	505
B1	Off	6.04	23.6	3.28	519
B2	On	6.04	23.6	3.28	519

B. Model

The test article for these experiments was a zero-incidence flat plate with an interchangeable (rigid or compliant) ramp to form a compression corner. The base of the model consisted of a 280 x 711 mm steel flat plate with a sharp leading edge and a 102 mm-wide channel along the centerline for inserts. Each of the ramps were fabricated from 15-5 PH/H1025 (AMS 5659) stainless steel and were placed 356 mm downstream of the leading edge to generate the flow compression. The rigid ramp measured 203 mm wide by 102 mm long and was 7.62 mm thick. The side edges were machined to a sharp point such that when the ramp assembly was inserted into the flat plate, the leading edge of the ramp was flush with the surface of the flat plate. Kapton™ tape was used to prevent throughflow beneath the ramp side extensions. The compliant ramp had the same general geometry as the rigid ramp, but a 76.2 x 88.9 mm rectangular cavity was machined out of the back, resulting in a 0.5-mm-thick clamped panel embedded in the surface of the ramp. As shown in Figure 1, the upstream edge of this plate was co-located with the corner of the compression ramp. The

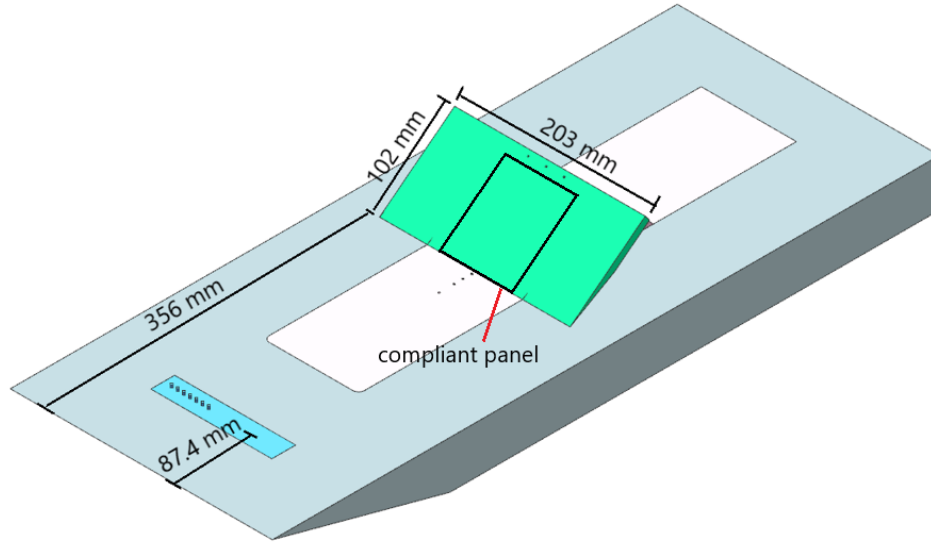


Fig. 1 Computer-aided rendering of the model with optional trips.

ramps were placed on interchangeable angled brackets to produce ramp angles of 10° , 20° , 30° , and 35° , producing SWBLI ranging from attached to fully separated.

To mitigate static-pressure-induced deformation of the compliant panel, a plenum box was designed to create a pressure-controlled environment on the leeside of the panel. The cavity generated by the plenum box and ramp was 15.7 mm deep and controlled by a pressure calibration unit which matched the back pressure with the static post-shock pressure on the flow side expected from inviscid theory. The panel and plenum box assembly with the hose fitting for pressure control are shown in Figure 2.

In select experiments (see Table 1), boundary-layer trips were placed 87.4 mm downstream of the leading edge in order to produce a fully turbulent flow over approximately half of the interrogation area of the ramp, allowing investigation of the panel response to a spanwise-nonuniform flow forcing. The trips had a diamond shape with a side length of 2.16 mm and were oriented 45° to the incoming flow. The trips protruded 3.05 mm into the flow and were pitched 6.6 mm apart. The placement of the trips was chosen based on an expected lateral spreading angle of approximately 3° [8].

On the flat plate, a flush-mounted, fast-response, piezoresistive Kulite™ pressure transducer (XCS-062) was placed 38.2 mm upstream of the compression corner along the centerline of the model. Both ramps were instrumented with three flush-mounted XCE-062 sensors located 96.5 mm downstream of the corner along the ramp, offset -19, 0, and 19 mm from the centerline. The plenum box was instrumented with two XCE-062 sensors to measure the pressure fluctuations inside the cavity. The pressure measurements were collected by three Dewetron TRION-2402-dSTG universal input modules at 200 kHz with an antialiasing filter. To verify the measurements from the infrared camera

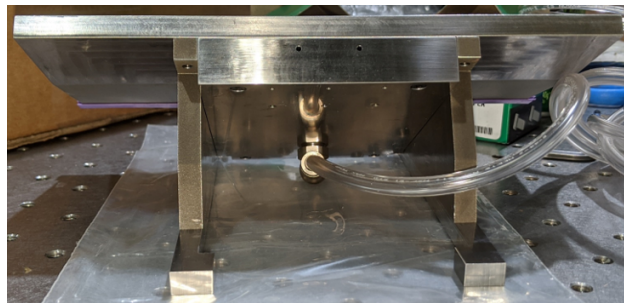


Fig. 2 Rear view of ramp with the plenum box.

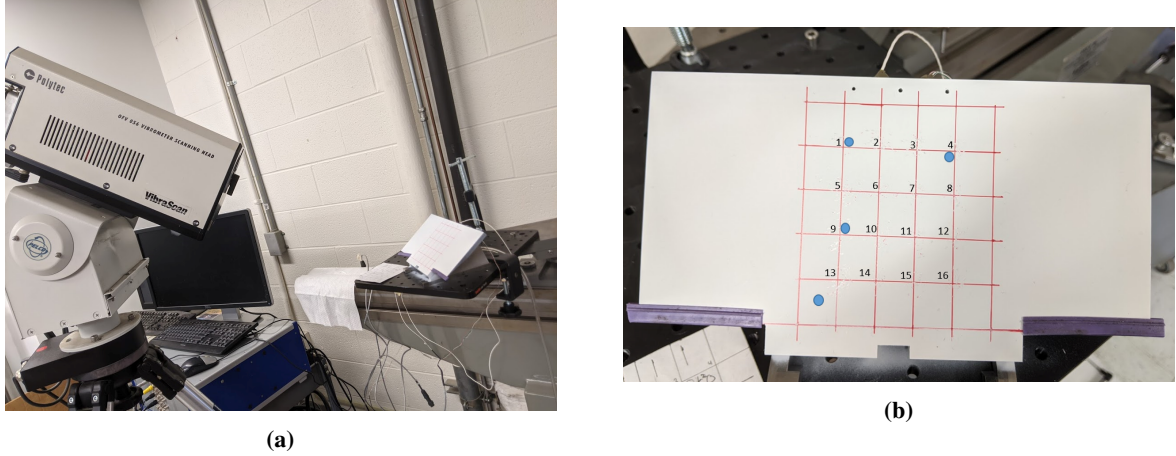


Fig. 3 (a) Plate and vibrometer setup. (b) Panel with vibrometer collection locations in blue and numbered tapping points.

arrangement to be discussed in Section II-D, two type-J beaded thermocouples were mounted flush with the surface of the rigid ramp, 3.81 mm on either side of the centerline, and 42.7 mm downstream of the compression corner. Three stick-on type-E thermocouples were placed on the leeside of the compliant panel, 37.3 mm downstream of the compression corner and -19, 0, and 19 mm from the centerline. The measurements from the thermocouples were collected at 50 Hz.

C. Pitot Rake

A pitot rake was used to determine the boundary-layer state along the centerline of the model at the compression-corner location (note that the ramp was removed for these experiments). The rake consisted of 12 stainless-steel stagnation probes, each with an outer diameter of ~ 0.58 mm and separated vertically by 1.35 mm for a total height of 16.2 mm. To allow for experimentation with the rake, the ramp was removed from the flat plate and a steel block, into which the rake was installed, was positioned in its place, flush with the surface of the flat plate.

D. Infrared Thermography

IR thermography was used to measure the surface temperature of the ramps. The surface of the entire model was coated with a thin layer of Rust-Oleum™ High Heat black paint, resistant to temperatures up to 1200°F. Benchtop calibration of the camera with a 15-5 PH/H1025 coupon coated in the black paint gave an emissivity of $\epsilon = 0.92$. A FLIR A655sc camera was used to measure the radiation emitted by the panel. Operated at a 640 x 480-pixel resolution and 50-Hz sampling rate, the camera exhibited an uncertainty of $\pm 2^\circ\text{C}$ for temperatures between -40°C and 150°C or $\pm 2\%$ of the reading for 100°C to 650°C .

E. Vibrometer Measurements

Post-campaign modal testing was used to characterize the panel natural frequencies at various pressure differentials. A Polytec PSV-300 scanning vibrometer was used to collect the data at 100 kHz at 4 discrete locations. The measurement locations were selected such that the points would not lie on nodes for the first six modes. The surface of the model was covered in a thin layer of Rust-Oleum™ High Heat white paint to maximize the diffuse reflection of the probing laser. The compliant panel was divided into an evenly spaced 5x5 grid producing 16 tapping points as shown in Figure 3. An impulse hammer with a hard nylon tip was used to excite the panel at each tapping point for each data collection point, resulting in a total of 61 sets of data for each pressure differential.

III. Results

A. Incoming Boundary-Layer State

Pitot-rake measurements were taken at the four conditions to produce a baseline understanding of the boundary-layer state at the compression corner. From the mean pitot pressures in Figure 4, it is apparent that the trips significantly increased the boundary-layer thickness for condition both conditions (note that we omit data taken from damaged probes located at $y = 2.7$ mm and $y = 14.85$ mm). The effect of the boundary layer trips on the surface temperature is shown in Figure 5, with the thermal images showing a clearly spanwise-nonuniform boundary layer. The rake appears to be at the edge of the tripped boundary layer at flow condition A2 whereas it is engulfed by the tripped boundary layer at condition B2. Note that the plate in front of the rake is made from aluminum and thus has a much higher thermal conductivity compared to the rest of the steel flat plate, resulting in the lower surface temperature (darker) region on the figures.

The thermal images indicate that the untripped flow at condition A2 is laminar and the untripped flow at condition B2 appears transitional. In earlier measurements at the same conditions [7], the boundary layer at the rake location was transitional at the lower Reynolds number and turbulent at the higher one; the authors believe that this discrepancy is due to the increased leading-edge bluntness caused by the application of the black paint, thus delaying transition on the flat plate.

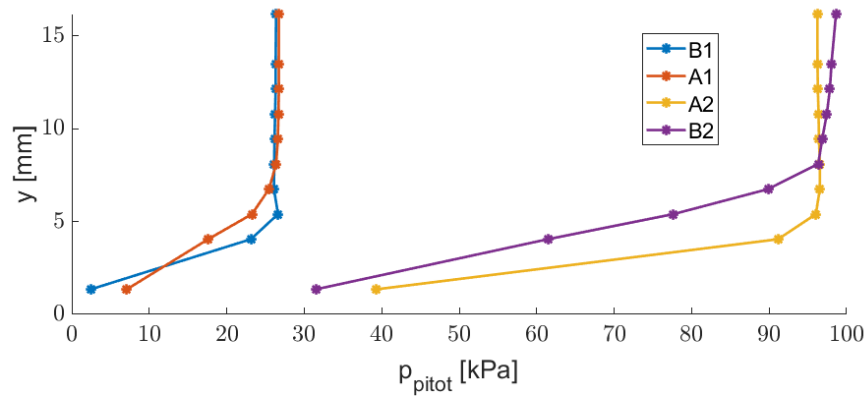


Fig. 4 Pitot rake pressure distributions.

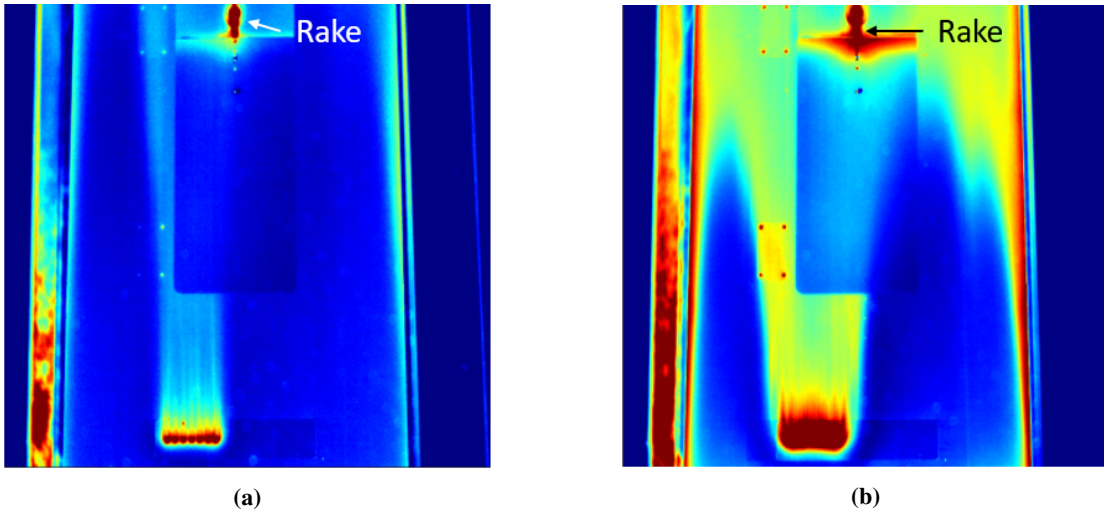


Fig. 5 Thermal images of the tripped boundary layer on the flat plate for conditions (a) A2 and (b) B2.

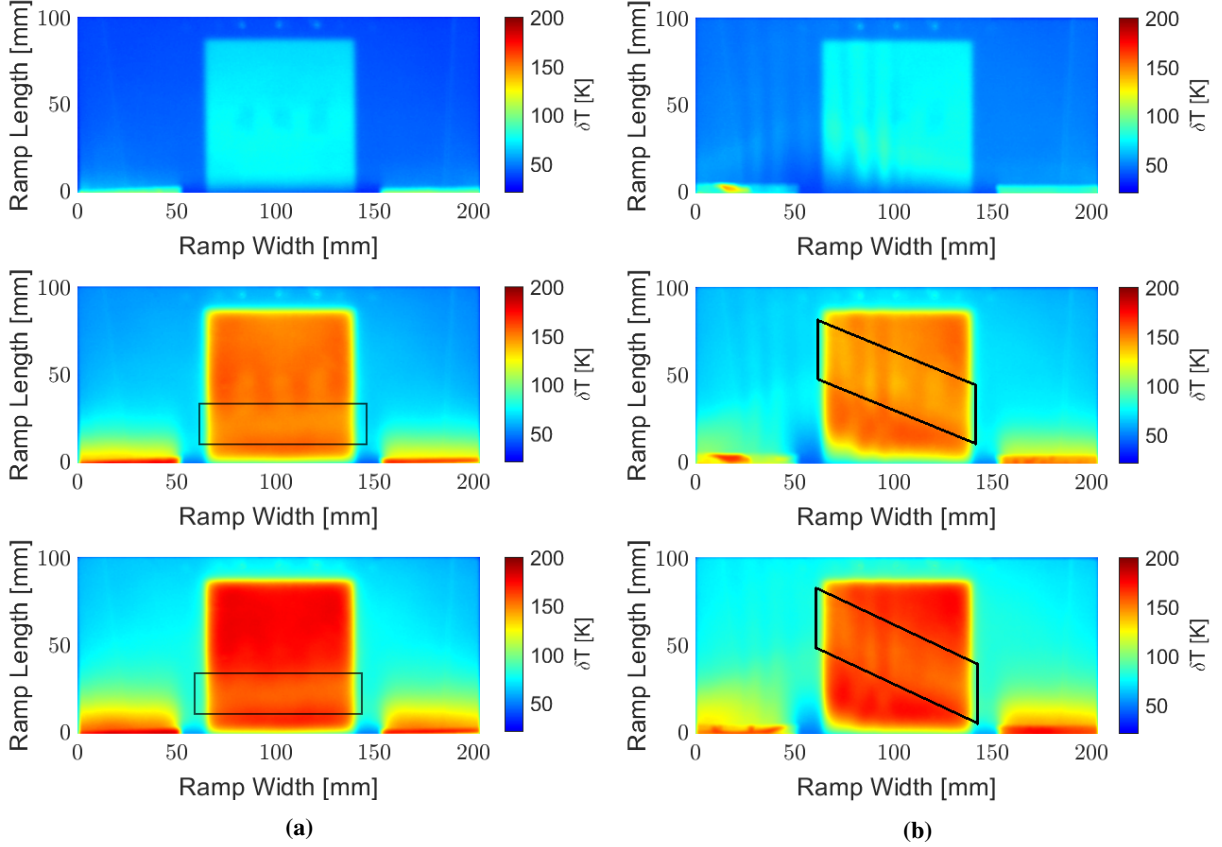


Fig. 6 Thermal images of the compliant ramp at 35° and conditions (a) B1 and (b) B2, acquired 0, 3, and 6 seconds after injection into the test section with the low-temperature zone indicated by the box.

B. Surface Temperature

Figure 6 shows the surface temperature distribution for the compliant ramp at 35° at conditions B1 and B2. An unexpected behavior occurs at this condition, in that there is a low-temperature zone at about 25% of the panel length for the untripped boundary-layer case. This behavior is also evident with the boundary-layer trips; however, rather than remaining constant along the span of the panel, the low-temperature zone is shifted downstream on the side of the panel affected by the boundary-layer trips. At 30° (Figure 7), this low-temperature region is shifted upstream, so much so that there is no longer a spike in temperature at the compression corner. As the ramp angle decreases, the temperature profile becomes almost constant across the entire panel. The upstream shift of the low-temperature zone as the ramp angle decreases follows the trend of boundary-layer separation and reattachment in ramp-induced SWBLIs [9]. At a ramp angle of 35°, Whalen et al. showed that the boundary layer is fully separated at the ramp corner whereas the separation is incipient at 30°. This would lead to the belief that the low temperature region marks the reattachment location of the boundary layer, since it travels upstream with the decreasing shock strength. However, when the tripped flow is introduced, the low-temperature region is pushed downstream, which is not what is expected when comparing a transitional and turbulent SWBLIs. Therefore, additional measurements will be necessary to explain this phenomenon.

Another feature that could affect the low-temperature zone is either a nominal static deflection or a buckled configuration, as the temperature difference between the panel and its support may be expected to promote buckling for $\Delta T > 26$ K, which is discussed in the following section. This buckling limit assumes an ideal case, however; since the panel supports are likely not perfectly clamped and the static pressure differential is not exactly zero, this buckling limit will be greater than 26 K. Figure 8 shows the half-span averaged temperature difference between the panel and the surrounding ramp at 35° and condition B2, where the temperature for the half of the panel in the tripped flow is shown in (a) and the half of the panel in the undisturbed flow is shown in (b). It is evident that already at injection, the panel is close to the critical temperature difference for the onset of buckling. However, for the first few seconds of the run, the temperature profile follows that expected from Stanton number distributions seen in other experiments [10]. Between 2

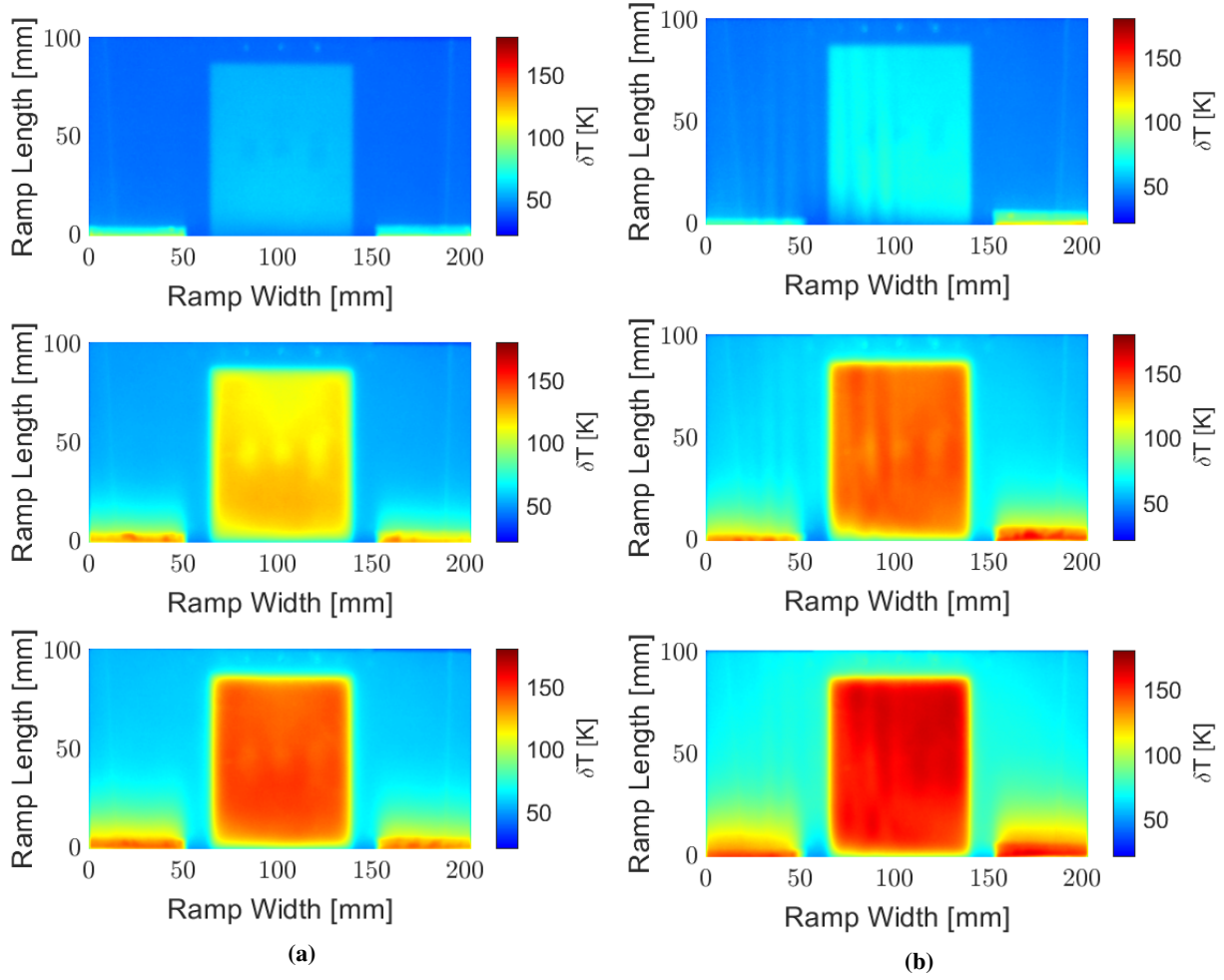


Fig. 7 Thermal images of the compliant ramp at 30° and conditions (a) B1 and (b) B2, acquired 0, 3, and 6 seconds after injection into the test section.

and 4 seconds into the run, the temperature profile changes, whereby the downstream half of the panel sees a greater temperature rise compared to the upstream half and the 25-33% chord length appears to have reached a limit, possibly indicating that the local adiabatic wall temperature is achieved at this location. A similar trend is visible in the 30° case, with a qualitative change in the temperature distribution somewhere between 2-4 seconds into the run (Figure 9). Here, however, a maximum temperature is achieved for the upstream third of the panel, showing the forward shift in the low-temperature region discussed previously. Without panel deflection data, it is difficult to conclusively say if these features are a result of the panel static deformation or buckling, or a response to the change in flow features. Figure 10 shows a representative case for the lower ramp angles where the panel does not reach the recovery temperature and the temperature distribution remains relatively constant (note that the spike in the data at about 50% of the panel length is due to a glare on the surface of the panel).

C. Modal Testing

The theoretical natural frequencies for a clamped plate with an aspect ratio $AR = 0.86$ were calculated using the methods of Freydin and Dowell [11]. The post-campaign panel frequencies were obtained using the vibrometer with a zero-pressure differential across the panel and are presented in Table 2, where the uncertainties in the experimental results are for a 95% confidence level. The differences in frequencies between the theoretical and measured values are most likely attributed to the panel not being perfectly clamped, as well as fabrication imperfections. Since the pressure distribution on the surface of the ramp is not uniform during a wind-tunnel test, we briefly explore the effects

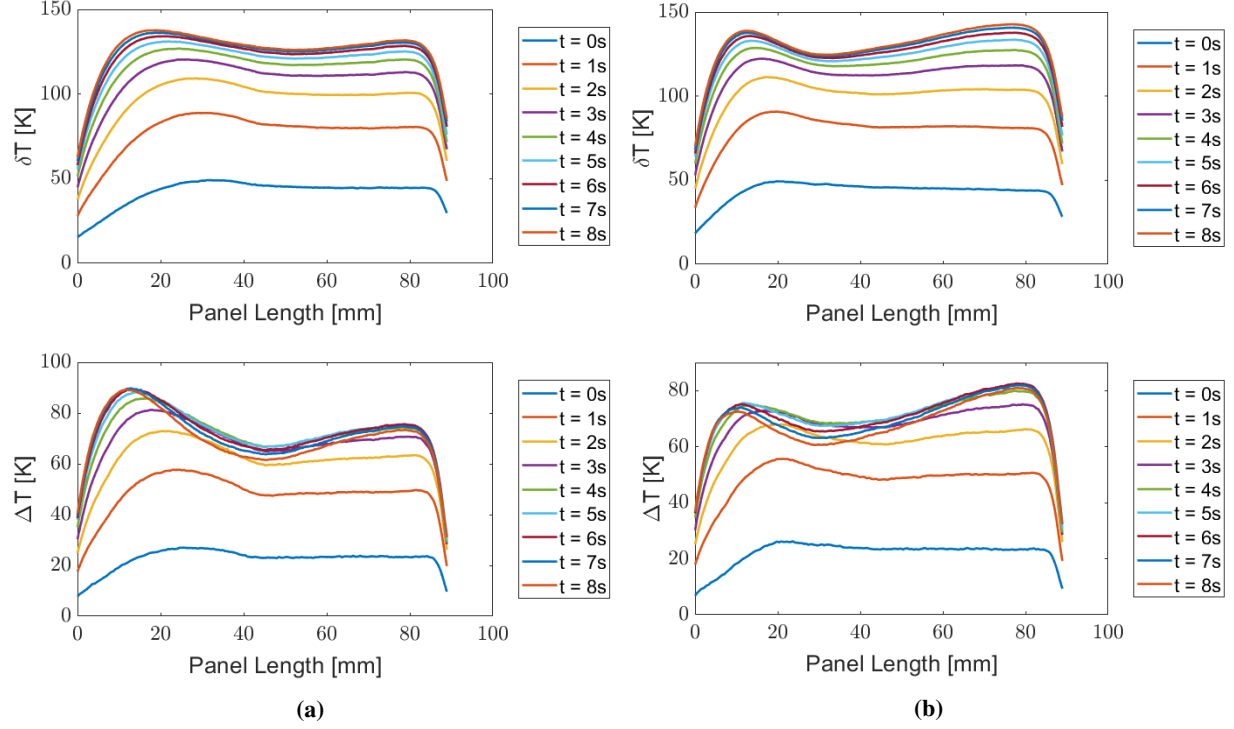


Fig. 8 Half-span averaged temperature distributions of the compliant ramp at 35° and condition B2 on the side (a) with and (b) without boundary layer trips.

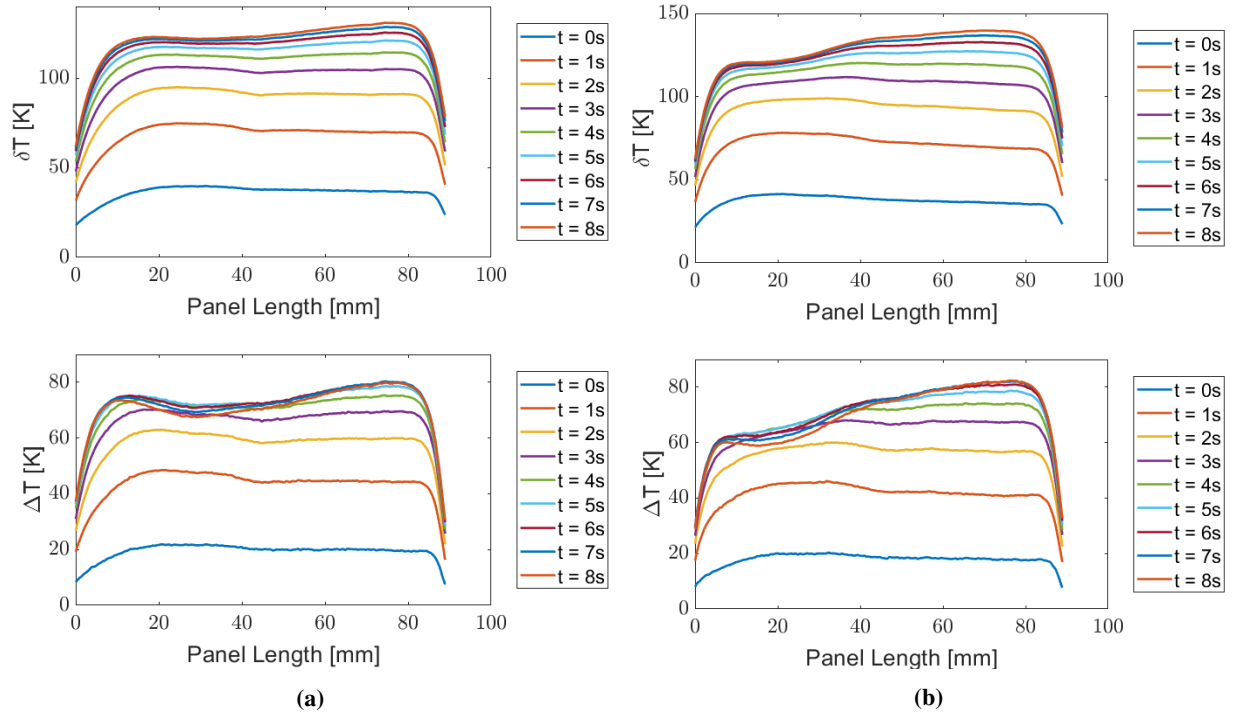


Fig. 9 Half-span averaged temperature distributions of the compliant ramp at 30° and condition B2 on the side (a) with and (b) without boundary layer trips.

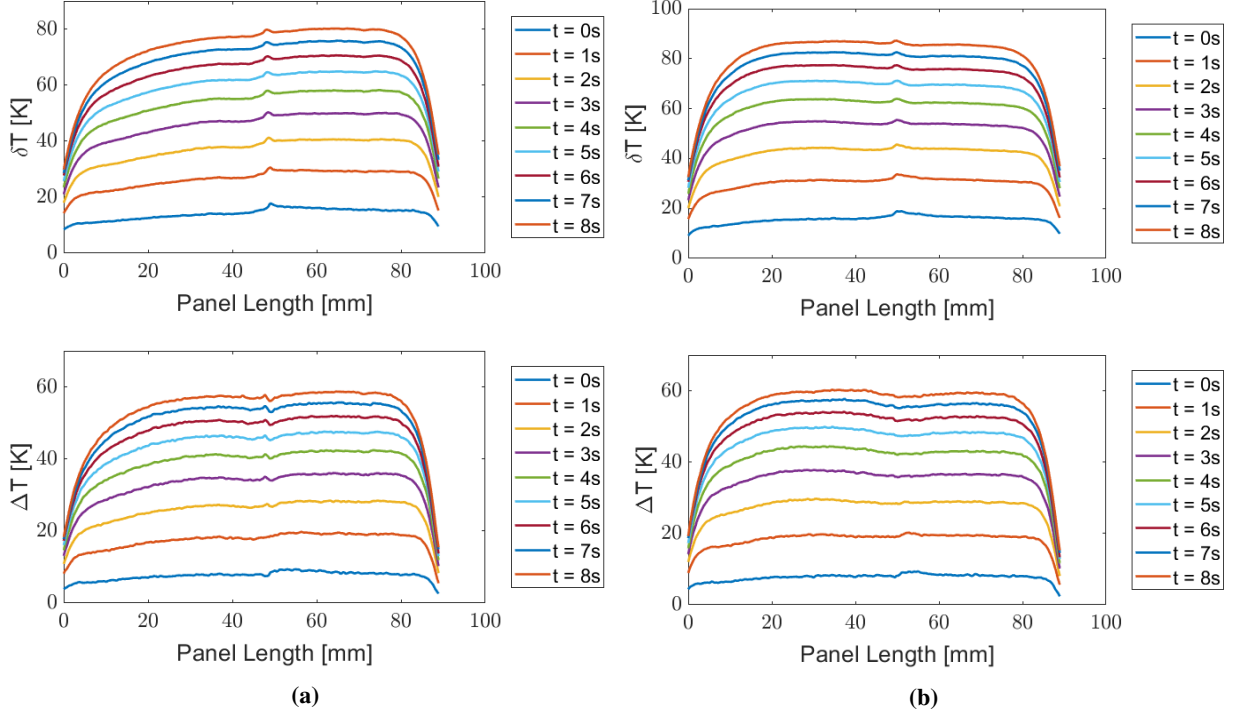


Fig. 10 Half-span averaged temperature distributions of the compliant ramp at 10° and condition B2 on the side (a) with and (b) without boundary layer trips.

of the pressure differential across the panel on the natural frequencies to elucidate some of the phenomena observed in wind-on conditions. The natural frequencies were found to increase with the increase in pressure differential (Figure 11), although they appear to exhibit different growth rates up to a pressure differential of approximately 50 kPa, which could be due to the unique interaction of the cavity and each natural mode [12]. As the pressure differential is increased from 50 kPa, the frequencies of the modes grow at roughly the same rate of $0.006 \pm 4.95 \times 10^{-4}$ kHz/kPa. The experimental results (markers) and theoretical results (dotted lines) are shown to be in good agreement.

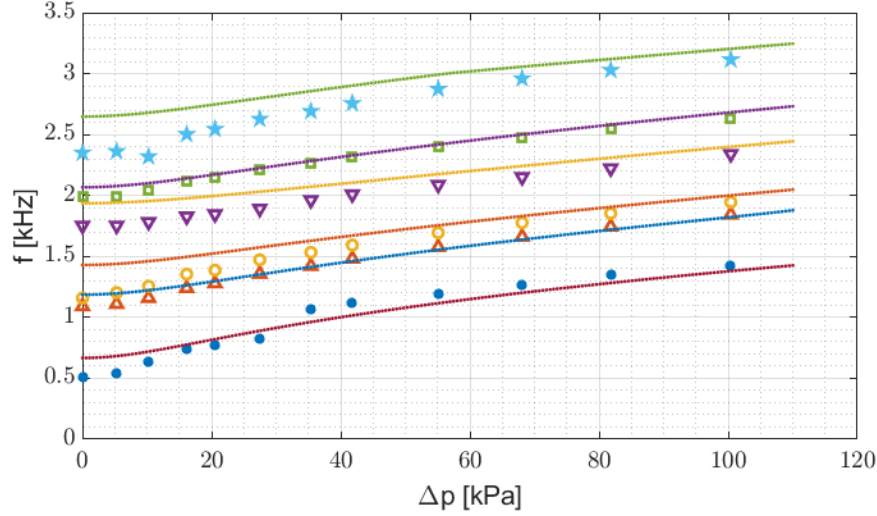
D. Panel Vibrations

Previous studies of a compliant panel under forcing generated by a SWBLI on a compression corner showed that a static deformation was caused by the pressure difference across the panel [4]. To study the panel with a negligible pressure differential, the plenum box on the leeside of the panel was pressurized to the post-shock static pressure calculated using inviscid theory. Using the methods outlined in Freydin et al. [13], simulations of the panel behavior at condition B1 show that the panel is expected to buckle under a thermal load generated by a temperature difference between the panel and its surrounding of approximately $\Delta T = 26$ K (Figure 12).

Since the panel vibrations produce variations in the static pressure inside the plenum box, the pressure transducers were used to study the natural frequencies of the panel during the experiments. Power spectral densities were calculated over 0.1 s time increments using Welch's method, for which an example is given in Figure 13. Unfortunately, at the lower ramp angles and all the runs at conditions A1 and A2, the variations in static pressure inside the plenum box were too small to detect discernible frequencies in order to look for a trend with the strength of the SWBLI. Figure 14a shows the temporally developing pressure spectra for the compliant ramp at condition B1. It is evident that the dominant low frequency modes are the spanwise symmetric (1,2) and (1,3) modes, at ~ 1.19 kHz and ~ 2.15 kHz, respectively, which supports the assumption that the baseline flow is essentially two-dimensional. On the other hand, when the trips are introduced, the modified SWBLI now produces a different forcing on half of the panel. This is evident in Figure 14b where the spanwise-antisymmetric (2,1) mode is now present throughout the run at ~ 1.42 kHz. A slight decrease in the frequencies of the lower two modes is visible while the higher mode appears to increase over time. To understand why these frequencies match the theoretical values closer than those from the modal testing, the pressure differential

Table 2 Compliant Panel Natural Frequencies for $\Delta p = 0$

Mode shape	$f_{theoretical}$ (kHz)	$f_{vibrometer}$ (kHz)
(1,1)	0.67	$0.51 \pm 6.61 \times 10^{-5}$
(1,2)	1.19	$1.09 \pm 1.15 \times 10^{-4}$
(2,1)	1.43	$1.16 \pm 2.50 \times 10^{-3}$
(2,2)	1.94	$1.75 \pm 9.27 \times 10^{-5}$
(1,3)	1.96	$1.99 \pm 2.16 \times 10^{-3}$
(3,1)	2.07	$2.35 \pm 1.81 \times 10^{-3}$

**Fig. 11 Natural frequencies of the first 6 modes vs Δp . The experimental results are given by the markers and the theoretical results by the dotted lines.**

is calculated using the downstream and cavity pressure transducers. The average pressure difference for the run at condition B1 is 5.97 kPa and at condition B2 is 6.74 kPa. Note, however, that the pressures upstream on the panel will be greater than those downstream, as was shown in other studies [10]. The observed frequencies in Figures 14 and 15 are consistent with a non-zero pressure differential based on the results in Figure 11 which show that the pressure differential across the whole panel is most likely less than 20 kPa.

To understand the panel vibrations, the frequencies of the panel are plotted against the panel-to-support temperature differential (ΔT) in Figure 15. Here, ΔT is the average of the difference in spanwise-average temperature of the panel and the support at the same streamwise location. The panel heats up rather rapidly, therefore the frequency transitions from Figure 14 are observed for $\Delta T > 60$ K in Figure 15. The (1,2) mode decreases as the temperature increases which is consistent with other findings [14]. However, the (2,1) mode, which shows an increasing frequency at the beginning of the experiment before appearing intermittently at lower frequencies (Figure 14b), seems to increase at a very shallow rate with respect to temperature in Figure 15b. Given that buckling is expected at the achieved temperatures, panel deformation could have an effect on the behaviors of each mode as the temperature increases. Due to the presence of the cavity, the acoustic frequencies must also be taken into account. For the given cavity geometry, and assuming the air in the cavity is at room temperature, the two lowest acoustic frequencies are calculated to be 2.00 kHz and 2.27 kHz. Since acoustic frequencies increase with the increase in temperature, it is more likely that what is thought to be the (1,3) mode is actually an acoustic frequency. However, without deformation data for the panel, it is difficult to conclude whether the ~ 2 kHz frequency is an acoustic or a structural frequency.

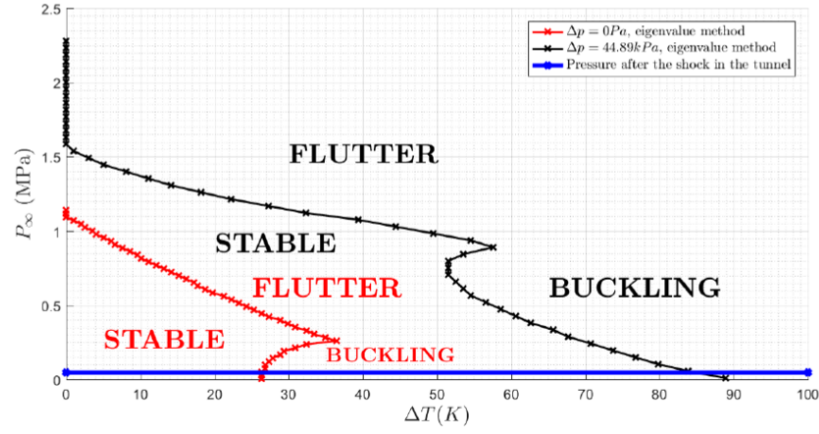


Fig. 12 Structural stability map for condition B1.

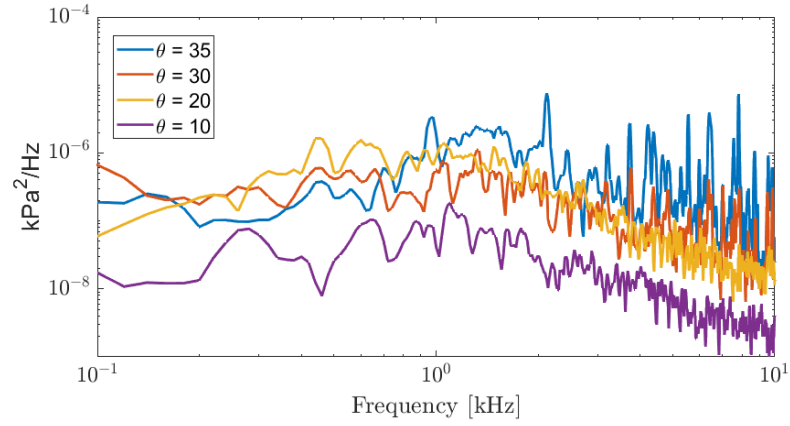


Fig. 13 Power spectral densities inside the plenum box for condition B2.

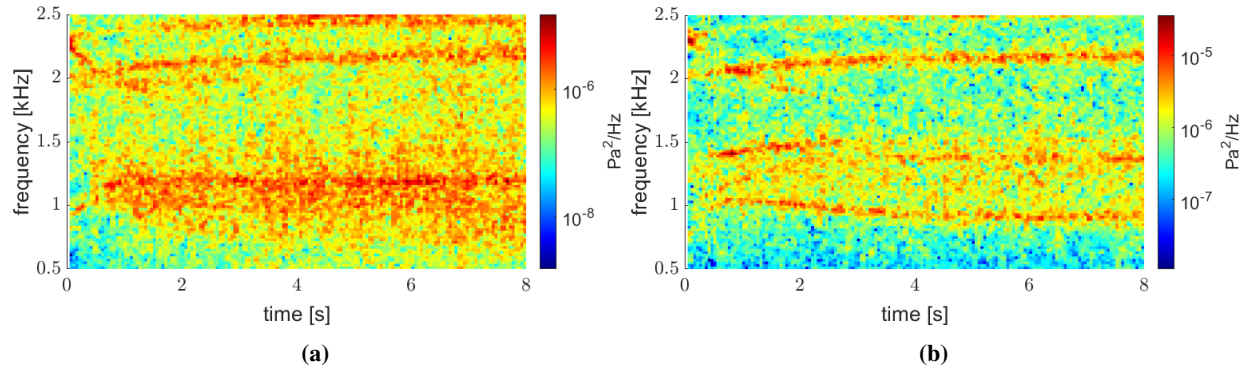


Fig. 14 Time-resolved PSD for the compliant ramp at $\theta = 35^\circ$ for (a) condition B1 and (b) condition B2.

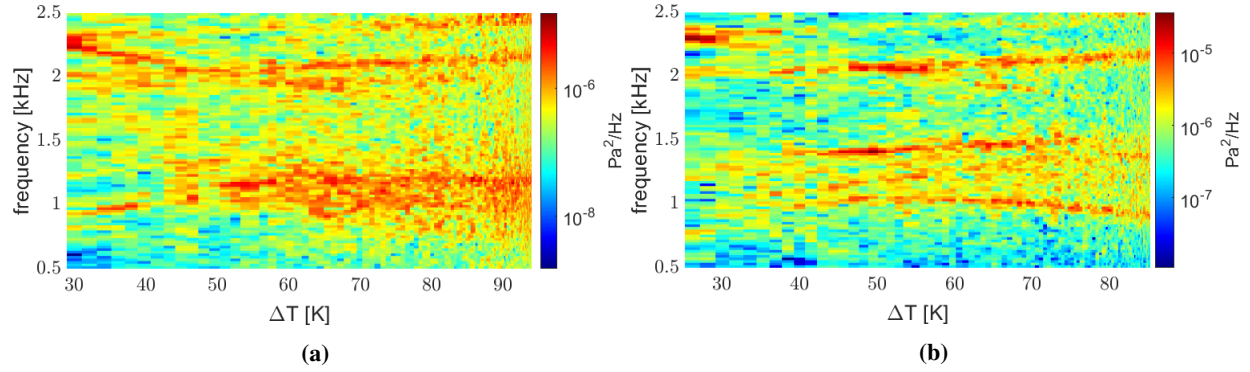


Fig. 15 Time-resolved PSD vs ΔT for the compliant ramp at $\theta = 35^\circ$ for (a) condition B1 and (b) condition B2.

IV. Conclusion

In this study, we conducted experiments on the fluid-thermal-structural interactions generated by compression-corner shock-wave/boundary-layer interactions at Mach 6 for a variety of ramp angles. A spanwise-nonuniform flow has been shown to excite spanwise asymmetric modes in the panel which were not present in the baseline flowfield. The natural frequencies of the panel are shown to decrease as the panel heats up which is consistent with other studies. Furthermore, it appears that panel buckling has a major role in the temperature profile of the panel. A continuation of these experiments using simultaneous IR thermography and photogrammetry will provide more information to better understand the effect of panel deflection and buckling on the temperature and vibration of the compliant structure. The analysis of the effect of static pressure difference across the panel show that the frequencies of each mode increase at different rates up to a certain pressure differential limit, after which, the frequencies increase at a steady rate.

Acknowledgments

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