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Backpressure unstart detection for a scramjet inlet based on information fusion

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ABSTRACT

The process of a two-dimensional hypersonic inlet from start to unstart is experimentally demonstrated in this article by recording the corresponding time history of wall static pressures. The careful analysis of pressure signals indicates that T8, located the upstream last ramp compression shock, is the optimum transducer for unstart detection because it can denotes obviously the start mode and unstart mode. The derivative-based detection developed in the current paper is a new and easy-implementation technique. Comparing it with other reported techniques including the STD-based detection and the spectrum-power-based detection, the derivative-based detection has no data to be stored and no expensive calculation benefiting the detection in real-time, and it can be achieved by an analog circuit in engineering. A particular of interest focuses on the detection of the non-oscillatory violent pattern. The information of pressure magnitude of T8 is introduced to eliminate the false detection in the non-oscillatory violent pattern. Apply the given detection method to six runs under different freestream conditions, and the results indicate that it can detect unstart in time and shows a good performance.

1. Introduction

Hypersonic inlet is an important part of a scramjet and it is used to achieve the compression of freestream; its starting mode is the prerequisite for the normal operation of a scramjet. However, almost every type of hypersonic inlet is subjected to an unstart phenomenon. In the existing flight tests, including CIAM/NASA in 1998 [1], Hypersonic Collaborative Australia/United States Experiment in 2007 [2], X-51 A in 2010 and 2011 [1], inlet unstarts occurred due to various reasons. Unstart phenomenon is undesirable because it causes a large drop of both engine thrust and specific impulse, even a flameout; thus it may cause a catastrophic damage during a hypersonic flight. What is more, inlet unstart caused by high backpressure leads to the violent oscillation of the shock system and the prominent fluctuations of pressure, which can lead to the destruction of an engine and even the failure of flight controls. Therefore, the unstart phenomenon should be avoided at any time in theory. But it is a challenge to avoid inlet unstart because in reality it may result from different factors, such as freestream disturbances, low operating Mach number, large angle of attack or improper fuel management. Therefore, it is particularly important to effectively predict and detect inlet unstart for a scramjet.

Much work has been done on the unstart process of hypersonic inlets to provide information for the detection, prediction, and control of unstart. Experimental investigation of the unstart process of a generic hypersonic inlet indicates that the shock train in an isolator moves upstream with the increase of backpressure, and once the leading edge of the shock train formed in the isolator

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[1] Data available online at http://defensetech.org/2011/06/15/second-x-51a-hypersonic-test-flight-ends-early/.

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Nomenclature

TR = throttling ratio
$A_{th,\mathrm{plug}}$ = throat area near plug
$A_{\mathrm{combustor}}$ = cross-sectional area of combustor
$h_{\max}$ = threshold of unstart onset
$h_{\min}$ = threshold of unstart retreat
t = time
x_{i} = the pressure measurement at time step i
$p(x)$ = the probability density of a signal
s_i = the log-likelihood ratio of probability densities
k = the current time
S_k = the cumulative of s_{i}
mi_k = the minimum until time k of S_{k}
ma_k = maximum until time k of S_{k}
h_i = the threshold for unstart onset
ha = the threshold for restart onset
t_{trigger} = unstart detection trigger time
t_{release} = unstart detection release time
L = window size
$P_{(i)}$ = the pressure of i time instant at T8

Subscript

i, k = Timestep counters

arrives at the entrance, unstart would occur [3],[4]. Thus, the distance from shock train leading-edge to the allowed most upstream location (such as the shoulder of inlet) can be used to characterize the stable margin of hypersonic inlet. The farther the distance is, the larger the stable margin of a hypersonic inlet is. The flow parameters changes notably by the compression effect of shock train, for example, the increase of static pressure. Le et al. [5] studied experimentally a Dual-Mode Scramjet Isolator, and power spectral analyses indicate that there is significant variation in the frequency content of the pressure signal upstream and downstream of the shock-train leading edge, suggesting that methods of shock-train leading-edge detection may be developed using pressure–time history characteristics other than the pressure magnitude. Many techniques [6] were developed to detect the location of shock train leading-edge in the isolator, in order to characterize the stable margin and prevent inlet unstart from occurring. Six methods—pressure ratio method, pressure increase method, standard deviation method, shock train location from frequency content, static pressure summation method and back pressure method—were considered to locate the shock train leading-edge [6], and the location of shock train leading-edge model was developed [7] by Hutzel. While majority detection methods were based on pressure distribution, the accuracy depends much on the number of the transducer which is constrained in practice. Chang et al. [8] used a genetic algorithm to optimize transducer locations in order to decrease the number of transducers. These techniques focus on the detection of shock train leading-edge in an isolator. In unstart prediction and detection aspects, the reported investigations are relatively few. Trapier et al. conducted experiments on supersonic inlet [9] and the study of the evolution in time of the energy levels corresponding to buzz frequencies indicated some precursor phenomena that can appear several tenths of seconds before the onset of buzz, then two change-detection algorithms were tested and proved their ability to predict unstart successfully [10]. These two techniques are based on the probability density function of pressure signal, so they need a large amount of calculation which detrimental to the detection in real-time. Wagner et al. [11],[12] investigated experimentally the unstart dynamics of a simplified inlet/isolator model in a Mach 5 flow and obtained some pressure data, which were used to test and compare three shock train leading-edge detection criteria for unstart detection: (1) a rise in pressure [13], (2) an increase in standard-deviation of the pressure signal at T2, and (3) a spectrum power increase in the 300–400 Hz frequency band of pressure at T4, by Srikant et al. [14] and the results indicated that the pressure-magnitude-based detection gives earlier unstart detection in most cases, and the spectral-power method shows a good sensitivity to onset of unstart. The authors believe that a combination of pressure-magnitude-based detection algorithm on T2 and a spectral-power based detection algorithm on T4 will provide a significantly improved and robust unstart detection technique for this flow configuration.

Although three unstart detection techniques, namely the pressure-magnitude-based detection, the STD-based detection and the spectrum-power-based detection were developed, there may be some better techniques for unstart detection. In addition, the experimental model is not a scramjet engine, but a simplified-geometry hypersonic inlet-isolator. The differences of flow structure between the inlet-isolator and the scramjet engine may bring some special issues for unstart detection. What is more, the three unstart detection techniques were studied only in a freestream condition of Mach 5, then whether they are feasible or not at different freestream conditions are unknown. To clarify these questions, we experimentally investigate the unstart process caused by a plug of a scramjet engine at three freestream conditions of Mach 4.5, 5.0 and 6.0. In Section 2, the experimental setup is described briefly and some typical experimental results are presented. In addition, the pressures histories are analyzed carefully to find the optimum transducer for unstart detection. Since the oscillatory characteristics of both start mode and unstart mode is distinct, a new and easy-implementation unstart detection based the derivative of pressure is developed in the Section 3. For this scramjet model, two novel unstart flow patterns including the mixed oscillatory pattern and the non-oscillatory violent pattern were observed and described by Chang [15]. These two special unstart flow patterns make unstart