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Technical Notes

Empirical Equation for Self-Starting Limit of Supersonic Inlets

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Nomenclature

A = area, m^2
M = Mach number
γ = specific heat ratio

Subscripts

c = cowl-lip section
t = inlet throat section

I. Introduction

FOR hypersonic inlets that operate over a large Mach number range and use a combination of external and internal compression, it must be ensured that inlets can self-start at takeover Mach number. An unstarted inlet captures less airflow with lower efficiency and higher aerodynamic and thermal loads compared with a started inlet. The starting problem was recently studied by many researchers [1–3].

The term started is used to denote operation under conditions where flow phenomena in the internal portion of the inlet do not alter the capture characteristics of the inlet [4]. An inlet can be unstarted by three reasons [4,5]:

1) The internal contraction is so large that the inlet is over-contracted to the point where the flow chokes at the inlet throat.

2) The back pressure is raised beyond the level that can be sustained by the inlet.

3) The formation of a large separated flow makes the flow choked. At high Mach numbers, the unstarted flowfield is usually characterized by a large separated region.

Self-starting indicates that the inlet will start without a change in inlet geometry. It is a significant feature in a fixed-geometry inlet design because it indicates that variable geometry is not necessary to restart the inlet . Preliminary estimates of the internal contraction ratio that will self-start can be obtained from the Kantrowitz limit [7]. This limit is determined by assuming a normal shock at the beginning of the internal contraction and calculating the one-dimensional isentropic internal area ratio that will produce sonic flow at the throat.

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For a perfect gas the internal contraction ratio of Kantrowitz limit can be calculated as follows:

$$\left(\frac{A_c}{A_t}\right)_{\text{Kantrowitz}} = \sqrt{\frac{\gamma+1}{2+(\gamma-1)M_c^2}}M_c^{(\gamma+1)/(\gamma-1)} \cdot \left(\frac{2\gamma}{\gamma+1}M_c^2 - \frac{\gamma-1}{\gamma+1}\right)^{1/(1-\gamma)} \tag{1}$$

where A_c denotes the area of cowl-lip section, A_t denotes the area of throat section, and M_c denotes the average Mach number of cowl-lip section.

According to some experimental data, van Wie [4] pointed out that the Kantrowitz starting limit becomes conservative at high speeds as a result of the assumption of a single normal shock, because the shock system of an unstarted hypersonic inlet has a higher pressure recovery compared with a normal shock. This conclusion is proved by more self-starting testing in recent several years. An empirical equation for self-starting limit of supersonic inlets is attempted to conclude based on these testing data.

II. Result

The self-starting characteristics of many inlets have been investigated by wind-tunnel testing. The self-starting ability of an inlet is usually proved by the restart of the inlet after a mechanically imposed unstart. These published experimental results are presented in Fig. 1. It must be revealed that some inlet obtained a much larger self-starting internal contraction ratio than Kantrowitz limit by many ways including the use of bleed, bypass ducts, fluid injection, and so on [8]; those experimental data are not plotted in Fig. 1. Furthermore, two self-unstarted experimental values are also supplied in this figure.

The testing presented in Fig. 1 includes three kinds of inlets: two-dimensional (2-D) planar inlet [5,9], sidewall compression inlet [10], and inward turning inlet [11–14]. They imposed unstart mechanically by three ways, corresponding to the three previously mentioned unstarted reasons, respectively: 1) increasing the internal contraction ratio by variable geometry [10,12], 2) raising the back pressure [9,11,13], and 3) increasing cowl-lip shock strength to produce large separation flow [5].

In [5,9,10,12], the maximum self-starting internal contraction ratio for a specific inlet at a certain freestream Mach number was obtained by translating or rotating cowl, respectively. Among of them, [5,12] have close average Mach number of cowl lip, but their maximum self-starting internal contraction ratios have a large difference. This result is caused probably by their different inlet geometry: a 2-D planar inlet was used in [5] and an inward turning inlet was used in [12], the latter had a highly swept leading edge, which is beneficial to supersonic spillage, so it had a larger maximum self-starting internal contraction ratio. Furthermore, a different way for imposing unstart mechanically is also a probable factor to bring the difference. Studies by Goldberg and Hefner [9] and Smart [11] have a close self-starting internal contraction ratio, though the former has a higher Mach number at cowl-lip section, because boundary-layer factor was considered in [9], and boundary layer covered 78% height of cowl-lip section at this operation.

According to the data of [10–12], it is found that there seems to be a polynomial law between the maximum self-starting internal contraction ratio and the average Mach number of the cowl-lip section, given as the following equation:

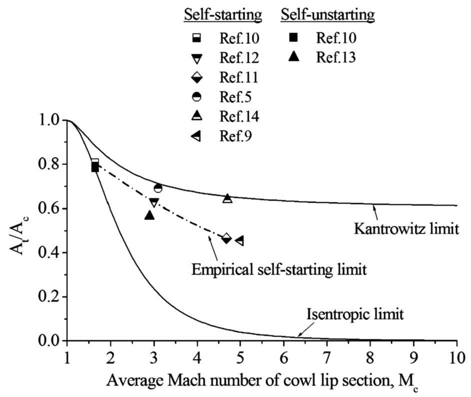

Fig. 1 Self-starting limits for supersonic inlets.

$$\left(\frac{A_c}{A_t}\right)_{\text{empirical}} = 0.933 + \frac{M_c}{6.87} + \frac{M_c^2}{40.9}(1.65 \le M_c \le 4.68) \qquad (2)$$

The preceding fit is plotted by the dash–dot line in Fig. 1.

III. Conclusions

Equation (2) presents the approximate relationship of maximum self-starting internal contraction ratio and average Mach number of cowl-lip section, which is probably useful for designing a supersonic inlet. Self-starting characteristics of an inlet can be influenced by many factors as inlet geometry, boundary layer, Reynolds number, etc., but it is certain that additional ways helping self-starting (like bleed, bypass ducts, fluid injection, and so on) should be considered if an inlet has a larger internal contraction ratio than the value limited by Eq. (2), especially when the Mach number of the cowl-lip section is lower.

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