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Active and Passive Control of Supersonic Impinging Jets

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The behavior of supersonic impinging jets is dominated by a feedback loop due to the coupling between the fluid and acoustic fields. This leads to many adverse effects when such flows occur in short takeoff and vertical landing aircraft, such as a significant increase in the noise level, very high unsteady loads on the nearby structures, and an appreciable loss in lifting during hover. In earlier studies, it was demonstrated that by using supersonic microjets one could disrupt the feedback loop that leads to substantial reductions in the aforementioned adverse effects. However, the effectiveness of control was found to be strongly dependent on the ground plane distances and the jet-operating conditions. The effect of various microjet control parameters are investigated in some detail to identify their influence on control efficiency and additional insight is provided on the physical mechanism behind this control method. Parameters studied include microjet angle, microjet pressure, and the use of microtabs instead of microjets. These results indicate that by choosing appropriate control parameters it should be possible to devise a control strategy that produces optimal control for the entire operating range of conditions of the supersonic impinging jet. Moreover, the experimental results provide convincing evidence of the generation of significant streamwise vorticity by the activation microjets. It is postulated that the generation of streamwise vorticity and its evolution in the jet flow might be one of the main physical phenomena responsible for the reduction of flow unsteadiness in impinging jets.

I. Introduction

THE flowfield generated by the impingement of high-speed lift jets on a surface usually results in a very unsteady flowfield. When such jets are used to generate direct lift in short takeoff and vertical landing (STOVL) aircraft during hover, this flow can lead to a host of adverse effects that can diminish aircraft performance. Significant among these are the substantially higher ambient noise levels in the jet vicinity and very high unsteady pressure loads on the ground plane and nearby structures. Frequently, the noise and the unsteady pressure spectra are dominated by high-amplitude discrete tones, which can further aggravate the sonic fatigue problem. These problems are more significant for supersonic impinging jets, the operating regime of the STOVL version of the Joint Strike Fighter.

A host of studies on the aeroacoustics of impinging jets by Powell,[1] Neuwerth,[2] Tam and Ahuja,[3] and more recently Krothapalli et al.[4] have clearly established that the self-sustained, highly unsteady behavior of the jet and the resulting impinging tones are governed by a feedback mechanism. The instability waves in the jet that originate at the nozzle exit grow as they propagate downstream toward the impingement surface, and the acoustic waves that are produced on impingement travel upstream and excite the nascent shear layer near the nozzle exit. For further details of the feedback loop, the reader is directed to Refs. 1–4. The acoustic properties of a single supersonic impinging jet flowfield have been investigated by a number of researchers[1–4] and continue to be the focus of current research. The emphasis is now increasingly on identifying control strategies to reduce the aforementioned problems associated with this flow because it is evident that such supersonic impinging jets need to be controlled to minimize their adverse influence on aircraft performance.

Powell[5] advocated viewing the resonant screech loop as a limit cycle. Four factors were considered in this limit-cycle approach: 1) the instability wave growth, 2) the shock–instability wave interaction, 3) feedback efficiency, and 4) stream disturbance creation efficiency. The last factor is commonly referred to as receptivity, and the second factor, in supersonic impinging jet, is the instability wave–impingement surface interaction.

Based on these ideas, a variety of control approaches have been proposed. One class of control methods attempts to manipulate the shear layer near the nozzle lip to make it less receptive to the acoustic disturbances, thus suppressing the formation of the feedback loop. This concept generally involves a modification of the nozzle geometry and the exit flow conditions using tabs[6] or nonaxisymmetric nozzle shapes.[7] Tabs have been shown to eliminate or reduce screech tones, where, for some cases, the mixing and shock-associated noise is reduced at lower frequencies but increases at higher frequencies. Using a nozzle with a design Mach number of 1.36, Samimy et al.[6] demonstrated that by using four tabs, the overall sound pressure level (OASPL) was reduced by about 6.5 dB when the jet was operated at an underexpanded mode. However, the reduction in noise was accompanied by a thrust penalty.

Another method for suppressing the feedback loop is to intercept the upstream and/or downstream propagating acoustic waves so that they cannot complete the feedback loop. Some attempts based on this idea have also been made. For instance, Karamcheti et al.[8] successfully suppressed edge tones in low-speed flows, which is governed by a similar feedback mechanism, by placing two plates normal to the jet centerline. Motivated by their work, Elavarasan et al.[9] used a similar technique to attenuate the feedback loop in a supersonic impinging jet by introducing a control plate just outside the nozzle exit. This passive control method resulted in a reduction in the near-field OASPL by about 6–7 dB.

Similarly, Sheplak and Spina[10] used a high-speed coflow to shield the main jet from the near-field acoustic disturbances. For a suitable ratio of the main jet and coflow exit velocity, they measured a reduction of 10–15 dB in the near-field broadband noise level in addition to the suppression of impinging tones. However, the mass flow needed for the coflow to achieve this makes this approach impractical. Shih et al.[11] successfully used counterflow near the nozzle exit to suppress screech tones of nonideally expanded jets. They were also able to obtain modest reductions in OASPL, approximately 3–4 dB, while enhancing the mixing of the primary jet.

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