TAILORING OF SHOCK DYNAMICS FOR IMPROVED TRANSONIC FLUTTER PERFORMANCE

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During vibration at transonic speeds, the oscillation of part-chord shock waves generates large unsteady pressures that, even at low reduced frequencies, may have a significant phase lag behind the wing motion. The subsequent changes to the wing's Generalized Aerodynamic Forces (GAFs), which describe the aerodynamic force generated on one natural mode due to the motion of another, greatly alters its flutter stability.

With increases in Mach number as little as 0.04, the phase of the shock motion in response to a given natural mode may change by over 180 degrees [1]. This causes a reversal in the values of those GAFs, in turn producing rapid changes in the flutter boundary and thus giving rise to the well known "transonic dip". The author's previous work in Refs. [2] & [3] provides a framework to identify which GAF changes are responsible for causing the transonic dip. This isolates the source of instability to the shock motion caused by the vibration of a specific natural mode.

However, the physical mechanisms that determine the magnitude and phase of this shock motion, i.e., *why* the shock moves in such a way to cause instability, are still poorly understood. Much debate exists over the relative importance of inviscid and viscous effects, as well the role of acoustic waves in enabling information transfer between the subsonic and supersonic regions [4]. The goal of this paper is to explain the changes in shock motion observed through the transonic dip, with the aim of identifying design changes that may control it.

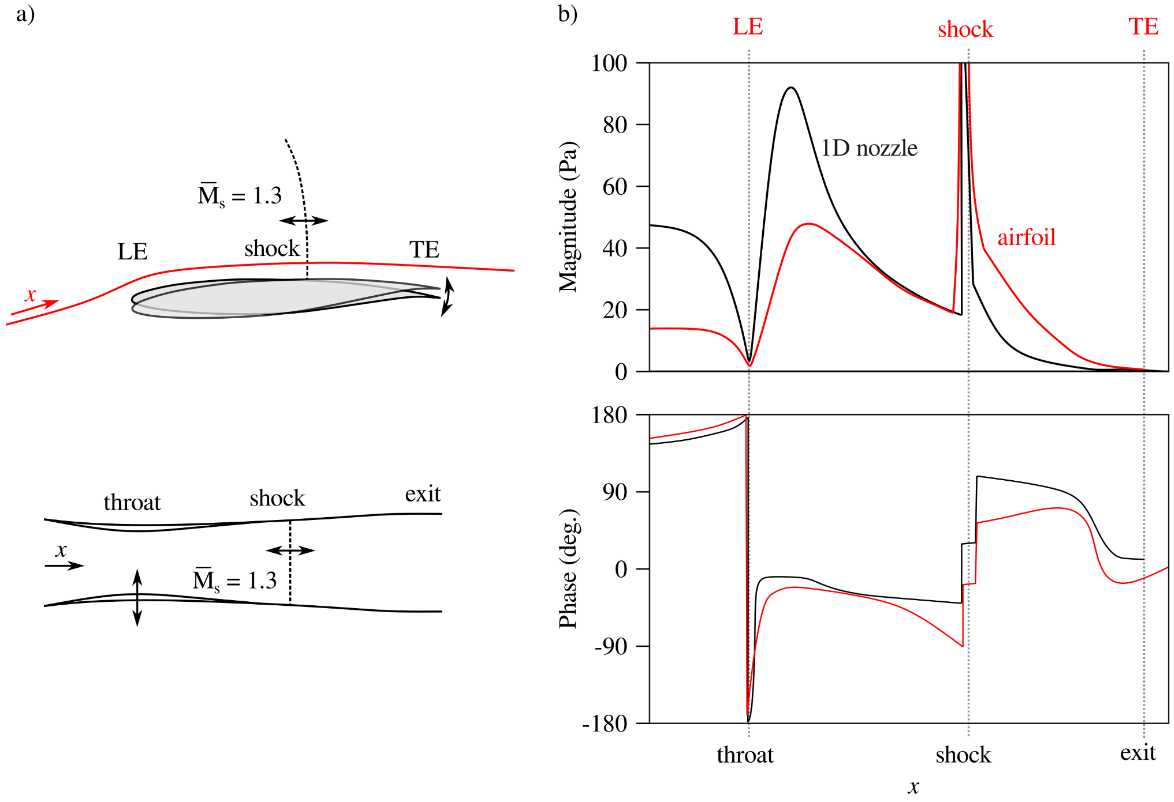

Fig. 1: Analogy between the unsteady transonic flow over a pitching airfoil and the 1D flow through a choked nozzle with a time-varying throat area: a) schematic of the airfoil and nozzle; b) magnitude and phase of the unsteady pressure along a streamline.

The key idea is an analogy shown to exist between a pitching airfoil and a 1D nozzle. Specifically, as illustrated in Fig. 1a, this work will demonstrate the unsteady transonic flow around a 2D pitching airfoil (top) is analogous to the 1D flow through a choked nozzle with a time-varying throat area (bottom). As the airfoil pitches back and forth, the flow acceleration around the leading edge changes, causing the Mach number upstream of the shock to vary. Similarly, as the nozzle throat area pulsates, its expansion ratio changes, also causing a variation in the pre-shock Mach number. In response, the shock wave (dashed black line) oscillates back and forth, with its motion constrained by the requirement of constant pressure at the trailing edge and nozzle exit.

To demonstrate the similarity in unsteady flow behaviour, the red line in Fig. 1b plots the magnitude and phase of unsteady pressure over a supercritical airfoil oscillating 0.2 degrees in pitch. These have been plotted along the streamline shown in red in Fig. 1a, using the output of a URANS simulation at a freestream Mach number of 0.73, angle of attack of 2 degrees, and a reduced frequency of 0.2. Meanwhile, the black line in Fig. 1b shows the unsteady pressure along a choked nozzle where the throat area pulsates by 0.5% at the same reduced frequency. The x axis has been scaled such that the nozzle throat, shock, and exit align with the airfoil leading edge (LE), shock, and trailing edge (TE), respectively. For these preliminary CFD results, the nozzle has been designed such that the steady pre-shock Mach number, $\overline{M}_s$, is the same as the airfoil at a value of 1.3, but no attempt has been made to match the rest of the steady Mach number distribution. The final paper will show better agreement is possible when this is also accounted for.

The general character of the two curves is remarkably similar. Notably, the magnitude of unsteady pressure drops to near zero at the LE and throat, while the phase flips by around 180 degrees. As expected, the phase also changes significantly on either side of the shock. However, this phase jump is much lower than the 180 degrees predicted by quasi-steady arguments. At the shock foot, the magnitude of unsteady pressure increases rapidly due to its motion. The phase of this shock-foot pressure variation, crucial for its influence on flutter through changing the GAFs, is seen to have an intermediate value between that of the upstream and downstream pressures.

This paper uses analytical solutions for the pulsating 1D nozzle to identify the physical mechanisms governing the shock motion on a pitching airfoil. The resulting expressions allow the magnitude and phase of the motion to be related to the frequency of oscillation and the airfoil's steady Mach number distribution. As the freestream Mach number increases, the subsequent changes to the steady flowfield are used to explain the changes in shock dynamics that lead to the transonic dip. Based on these results, it will be shown how an airfoil can be aeroacoustically "tuned" to control its shock motion through subtle changes in its profile. This could potentially provide a powerful means by which designers may improve transonic flutter performance.

References

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