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Self-sustained flow-acoustic interactions in airfoil transitional boundary layers

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14. ABSTRACT
This project conducted complementary experimental and numerical studies of flow-acoustic resonant interactions in transitional airfoils and their
impact on airfoil surface unsteady pressure and acoustic signature. The symmetric NACA-0012 airfoil and the slightly cambered SD7003 airfoil at
moderate incidence were tested in the free-jet anechoic wind tunnel of Ecole Centrale de Lyon. Measurements of wall pressure, far-field acoustic
pressure and velocity fluctuations using the hot-wire anemometry were conducted. In addition, advanced post-processing techniques were applied
High-accuracy numerical studies focused on selected transitional-flow regimes for NACA-0012 and SD7003 airfoils for which experimental
measurements recorded strong flow-acoustic resonant interactions characterized by multiple-tone acoustic spectra. Numerical studies employed a
6th-order Navier-Stokes solver implementing low-pass filtering of poorly resolved high-frequency solution content to retain numerical accuracy.

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Final Report

The current project addressed flow-acoustic resonant interactions in transitional airfoils using complementary experimental and numerical studies.

The symmetric NACA-0012 airfoil and the slightly cambered SD7003 airfoil at moderate incidence were tested in the free-jet anechoic wind tunnel of Ecole Centrale de Lyon. A thin and cambered Controlled-Diffusion (CD) airfoil with a rounded trailing edge has also been investigated for comparison. The emission of tones was attributed to the developing instability waves associated with transitional flow regimes in the boundary layers involving thin separation areas. For all tested airfoils multiple tones were observed. Tracking the dominant tone at increasing flow speed produces the so-called ladder-type tonal structure. The experiment also included unsteady wall-pressure measurements using the remote-microphone-probe technology and single hot-wire anemometry in the boundary layers. All measured quantities exhibited the tonal spectral content. The hot-wire results clearly showed the separation areas, possibly on both sides of the tested airfoils depending on the angle of attack. The main experimental observations can be summarized as follows:
(i) A fine-scale and low-level background turbulence in the external flow is able to deactivate the acoustic feedback in the same time that the boundary layers remain laminar and unstable. In this case the instability waves radiate without amplification of tones, producing a spectral hump. The feedback loop is essential for tone generation.
(ii) By performing the time-frequency analysis of the far-field pressure signals various regimes of tonal instability wave radiation have been identified depending on airfoil design, angle of attack and more essentially depending on flow speed (equivalently Reynolds number). These regimes distinguish from each other by the stationarity of the emission of tones. Lowest speeds rather correspond to a regime in which the flow switches between two states, each of which corresponds to a dominant tone. Slightly higher speeds lead to the simultaneous emission of two tones. In both regimes the tones superimpose on a bell-shaped hump and the tones emerge from a series of regularly spaced frequencies. At even higher flow speeds the hump broadens and multiple tones are simultaneously observed with some intermittency of the sound emission.
(iii) Bicoherence analysis was conducted, confirming the phase coupling between multiple tones and possible nonlinear effects.
(iv) Tripping on one side forces transition to turbulence but instability wave radiation, including multiple tones and the ladder-type structure, can still be observed. This shows that all features involved in the underlying physics are associated to the only side still laminar/transitional. Tripping both sides totally suppresses instability wave radiation.
(v) Coupling between the instability waves developing on both sides of an airfoil without tripping still needs to be further investigated, especially for symmetric airfoils at zero angle of attack, because residual asymmetry is unavoidable in practice.
(vi) Comparisons with other related works of either experimental or numerical nature show significant discrepancies. The latter are attributed to installation effects that make the details of the flow in wind tunnel testing very dependent of the nozzle design and flow-width to chord length ratio.
(vii) Simple analytical noise predictions using a deterministic version of Amiet's trailing-edge noise model and measured wall-pressure as input data have been found compatible with the far-field measurements.

Overall, the joint analysis of far-field sound, unsteady wall pressure and velocity fluctuations proved that the origin of instability-wave radiation can be identified without ambiguity, at least for the SD7003 airfoil. An extended experimental database has been built, the analysis of which is still in progress.

Concurrently, high-accuracy 2D and 3D (ILES) numerical experiments were conducted to investigate the phenomenon. A high-fidelity viscous solver along with the linear-stability and acoustic propagation codes were employed to predict and examine the airfoil boundary-layer dynamics including statistical moments, instability growth rates and surface pressure spectra, as well as the airfoil acoustic radiation in the far field. The following summarizes the outcomes of the numerical studies:

(i) Major part of the work focused on validating and comparing unsteady responses of NACA-0012 and SD7003 airfoils for selected flow regimes taking advantage of the experimental data.

(ii) High-accuracy simulations and linear stability analyses were implemented for NACA-0012 airfoil for flow regimes with different angles of attack and Reynolds numbers showing transition between tones-producing and no-tones-producing flow regimes. The parametric study was carried out for angles of attack ranging from $\alpha=0^\circ$ to $\alpha=12^\circ$ (with fixed $Re=180{,}000$), and for Reynolds numbers between 144,000 and 324,000, with fixed $\alpha=2^\circ$.

(iii) The results of the parametric studies clearly indicate that the rapid growth of the boundary-layer disturbances is associated with the presence of separation regions (i.e., laminar separation bubble, LSB) on either side of the airfoil. The switch from the slowly-growing Tollmien-Schlichting (T-S) waves (associated with the boundary-layer viscous effects) to the fast-growing Kelvin-Helmholtz (K-H) type waves (associated with the velocity gradients in the detached shear layers) is a necessary condition for the strong multiple-tones-producing flow-acoustic interaction, but the latter also depends on the ability of the convected mode to sustain its presence and the reached amplitude to the trailing edge for the efficient acoustic scattering process to take place. Thus, while distinct tones were produced for $\alpha\leq6^\circ$, the tones disappeared at higher angles of attack due to the LSB migration towards the leading edge and the resulting inability of the established but detached vortical structures to strongly interact with the trailing edge. On the other hand, for a fixed angle of attack, the increase in the flow Reynolds number was associated with LSB shrinking on the suction side and thus the increasingly dominant contribution of the amplified instabilities on the pressure side to the tonal generation.

(iv) The obtained results stressed the superposition of two phenomena in the tonal noise generation process for transitional airfoils. The dominant mode radiates at the shedding frequency naturally selected by the vorticity dynamics at the trailing edge and its pattern of shedding into the wake. Another tone-selecting mechanism is the acoustic feedback determined by matching the phases of the acoustic and vortical (instability) modes. Only the frequencies that are “cut-on” by the feedback-loop mechanism *and* appear to be the nearest to the shedding tone are clearly observed in the acoustic spectra. This points to the "dual-resonance" phenomenon as both the acoustic shedding and the acoustic feedback-loop process overlap and enhance each other. Such superposition also explains the dual-ladder tonal structure as the two mechanisms have different tonal frequency scaling with respect to the flow velocity.

Further details of the project efforts and results are included in several conference and journal papers published during the 3-year project, with further publications expected in the near future.

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Abstract

Th s project conducted comp ementary exper menta and numer ca stud es of f ow-acoust c resonant nteract ons n trans t ona a rfo s and the r mpact on a rfo   surface unsteady pressure and acoust c s gnature.

The symmetr c NACA-0012 a rfo   and the s ght y cambered SD7003 a rfo   at moderate nc dence were tested n the free-jet anecho c w nd tunne of Eco e Centra e de Lyon. Measurements of wa   pressure, far-f e d acoust c pressure and ve oc ty f uctuat ons us ng the hot-w re anemometry were conducted. In add t on, advanced post-process ng techn ques were app ed, such as the t me-frequency ana ys s and the b coherence n order to h gh ght some non- near features and/or nterm ttency. Three reg mes of no se em ss on were dent f ed depend ng on the conf gurat on and f ow ve oc ty. An extens ve exper menta database was bu t to be further exam ned n the future stud es.

W th the c ean upstream f ow cond t ons, the exper ments revea ed a adder-type structure of acoust c tones w th dua ve oc ty dependence. They corresponded to the rungs w th frequency f ~U^0.8…0.85 re ated to the amp f ed nstab   ty-wave tra   ng edge scatter ng, and the effect ve y produced vort c ty shedd ng correspond ng to the dom nant frequenc es of each rung sca ed w th fs ~U^1.5 . A rfo   surface tr pp ng

revea ed d fferent eve s of contr but ons to the resu t ng pressure spectra nduced by pressure- or suct on-s de boundary- ayer nstab t es depend ng on f ow ve oc ty.

Numer ca resu ts dev ated from measurements n pressure spectra but revea ed a pattern of mu t p e tones match ng we w th the formu as for the acoust c feedback oop mechan sm. The effect of weak upstream turbu ence on the rad ated sound was stud ed exper menta y and numer ca y. The ma n effect was to suppress a tones assoc ated w th acoust c feedback and the 0.85-power adder-type structure. But the ma n trace of the hump correspond ng to the pr mary vort c ty-shedd ng mechan sm of the tra ng-edge acoust c rad at on was preserved and st fo owed the 1.5-power aw.

H gh-accuracy numer ca stud es focused on se ected trans t ona -f ow reg mes for NACA-0012 and SD7003 a rfo s for wh ch exper menta measurements recorded strong f ow-acoust c resonant nteract ons character zed by mu t p e-tone acoust c spectra. Numer ca stud es emp oyed a 6th-order Nav er-Stokes so ver mp ement ng ow-pass f ter ng of poor y reso ved h gh-frequency so ut on content to reta n numer ca accuracy and stab ty over the range of trans t ona f ow reg mes. The compar son of numer ca vs. exper menta resu ts for the se ected cases emphas zed cha enges nherent to the pred ct on of h gh y sens t ve f ow reg mes w th often- nterm ttent tona sound rad at on pattern. Numer ca pred ct ons are further supp emented by the near-stab ty resu ts prov d ng further ns ght nto the boundary- ayer nstab ty-wave dynam cs contr but ng to the mutua enhancement of the vort c ty-shedd ng and the feedback- oop re ated acoust c scatter ng phenomena. An extended parametr c study exam ned the effects of the ang e of attack and Reyno ds number to e uc date phys ca mechan sms assoc ated w th trans t on from tones-produc ng to no-tones-produc ng f ow reg mes.

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Archival Publications (published) during reporting period:

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Go ubev, V.V., Nguyen, L., Roger, M., and V sba , M.R., (2011), “On Interact on of A rfo Lead ng and Tra ng Edge No se Sources n Turbu ent F ow,” AIAA Paper 2011-2859, 17th AIAA/CEAS Aeroacoust cs Conference, Port and, June 2011.

Go ubev, V.V., Nguyen, L., and V sba , M.R., (2011), “H gh-F de ty S mu at ons of Trans t ona A rfo Interact on w th Upstream Vort ca Structure,” AIAA Paper 2011-394, 49th AIAA Aerospace Sc ences Meet ng and Exh b t, Or ando, January 2011.

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