Unsteady Lift due to the Interaction of Incidence Turbulence with an Airfoil

Sparsh Sharma[1], Ennes Sarradj[2], Heiko Schmidt[1]

[1] *Fachgebiet Technische Akustik, BTU Cottbus-Senftenberg, 03046 Cottbus, E-Mail: sparsh.sharma@b-tu.de*
[2] *Fachgebiet Technische Akustik, TU Berlin, 10587 Berlin, E-Mail: ennes.sarradj@tu-berlin.de*

Introduction

The acoustic signature from an airfoil downstream an incoming turbulent flow is a complex mathematical phenomenon which requires solving the nonlinear governing equations with higher resolutions. The problem is illustrated in Fig. 1. With the advent of high computing resources, it's possible, but at a cost of higher calculation time. For the preliminary analysis in the design process, a method is needed to calculate unsteady-lift due to the airfoil-turbulence interaction with the following characteristics:

- fast and accurate
- need minimum computing resources
- compares more characteristics trade-off or parametric study

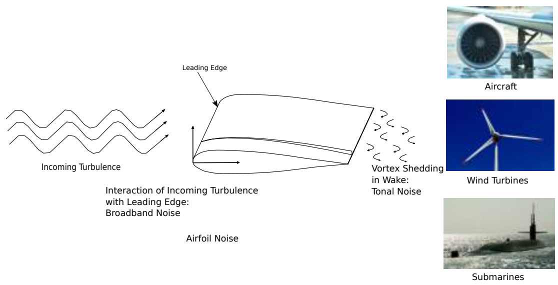

Figure 1: Incidence turbulence interacting with the leading edge of an airfoil

Unsteady Effects

By the definition, an unsteady flow is one where the flow field variables at any point are changing with time which means all the aerodynamic parameters fluctuate with time too, and are certainly the inhibitors of all the disturbances which causes the generation of noise from an airfoil. It is instructive to recall the major historical development in the unsteady aerodynamics. Standard work by Karman, Sears, Amiet etc. shows that the presence of unsteady lift or pressure fluctuation over the lifting surface is the main cause of the noise generation. In 1922, Prandtl[1] suggested to neglect the influence of viscosity while treating the problem of incompressible flow past an oscillating airfoil, and thus to take Laplace equation as governing equation. It was pointed out that every change in the lift must be accompanied by the detachment of a vortex from the airfoil's trailing edge.

As it is shown in Fig-1 that the incoming turbulent eddies upstream the airfoil strikes with the leading edge of the airfoil and this is heard as noise; whereas because of the boundary layer growth chordwise, the vortex shedding takes place which is another source of noise. An important parameter, reduced frequency, k, was introduced by Birnbaum[2],

$$k = \omega c/u$$

where k is reduced frequency, c is the chord length and u the flow speed. This parameter is a measure of unsteadiness. When an oscillating airfoil sheds a vortical wake with a certain wavelength, the reduced frequency compares this wavelength with the airfoil chord because during one oscillation a vortex shed from the trailing edge travels the distance u/w. This means, the higher the reduced frequency the smaller the wavelength.

- Steady state aerodynamics, $k = 0$
- Quasi-steady aerodynamics, $0 \leq k \leq 0.05$
- Unsteady aerodynamics, $k > 0.05$ [$k > 0.2$ is considered highly unsteady

Methodology

To mathematically derive the problem, Potential theory for unsteady flow[3] and Panel method[4] is used. The nobility of the work is to have the least assumptions and account for:

- finite thickness of the airfoil
- high subsonic speeds
- deformation of the airfoil
- cross wind effects

Fig. 2 shows the steps taken to model the incidence turbulence. Sources and vortices are used as the singularities. The wake is modelled using the Helmholtz circulation theorem[5]. This leads to the calculation of unsteady pressure fluctuation on the surface of the airfoil, which can further, be used to calculate the noise parameters using the acoustic analogies.

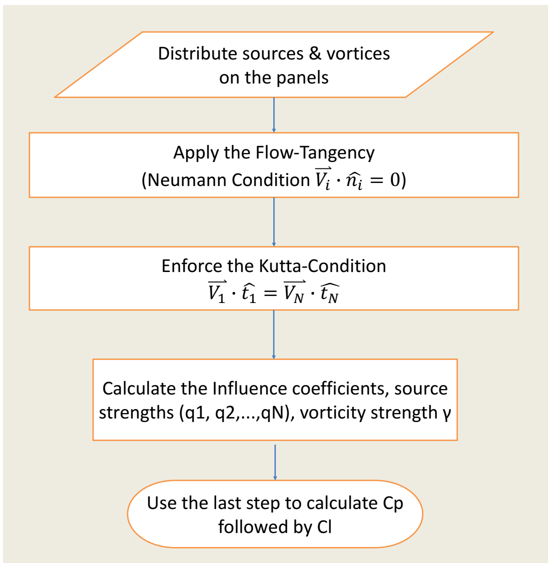

Figure 2: Flowchart of the steps

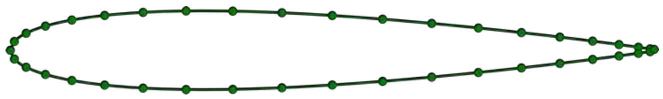

Figure 3: Representation of smooth airfoil with nodes and panels

Figure 3 illustrates the representation of a smooth surface by a series of line segments. The numbering system starts at the lower surface trailing edge and proceeds forward, around the leading edge and aft to the upper surface trailing edge. *N*+1 points define *N* panels.

$$\phi = V_\infty(x\cos\alpha + y\sin\alpha) + \sum_{j=1}^{N} \int_{panel\ j} \left[\frac{q(s)}{2\pi}\ln r - \frac{\gamma}{2\pi}\theta\right] dS$$

The approach (depicted in Fig. 4) is to

1. break up the surface into straight line segments,
2. assume the source strength is constant over each line segment (panel) but has a different value for each panel
3. the vortex strength is constant and equal over each panel

Roughly, think of the constant vortices as adding up to the circulation to satisfy the Kutta condition. The sources are required to satisfy flow tangency on the surface (thickness).

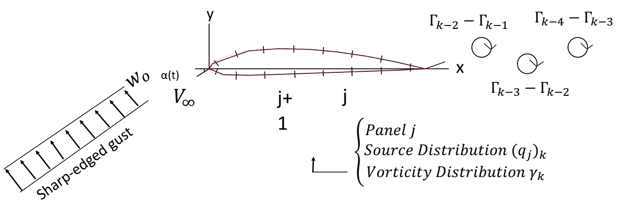

Figure 4: Extension of the panel method for unsteady-flow

Flow tangency boundary condition

A constant vortex strength $\boldsymbol{\gamma}$ will be added to each panel (all panels have the same, constant vortex-sheet strength). The flow tangency boundary condition is applied at every panel center:

$$0 = \vec{V} \cdot \vec{n_i} = \frac{\partial}{\partial n_i}\{\phi(x_{ci}, y_{ci})\}$$

Enforcing the Kutta Condition

In case of steady flow, the Kutta condition is expressed as the zero velocity at the trailing edge or no vortex sheet or no pressure difference at the wake region.

In case of unsteady flow, however, there is a nonzero velocity at the trailing edge and non-zero vortex sheet at the near wake. Therefore, the unsteady Kutta condition is expressed as the zero-pressure difference at the wake:

$$\frac{d\Gamma_a}{dt} + \frac{\partial}{\partial t}\int_b^\infty \gamma_w(\xi, t)d\xi + U\gamma_w(x,t) = 0$$

Steady-State Results

This section shows the steady-state results. The entire code is written in Python, and it is planned to write the steady code in the first phase and then develop it for the unsteady-flow conditions. Following figures show the airfoil discretization, streamlines around the airfoil, and pressure field around the airfoil. The computations will be validated using the experimental data from the wind tunnel tests at the university's acoustic facility.

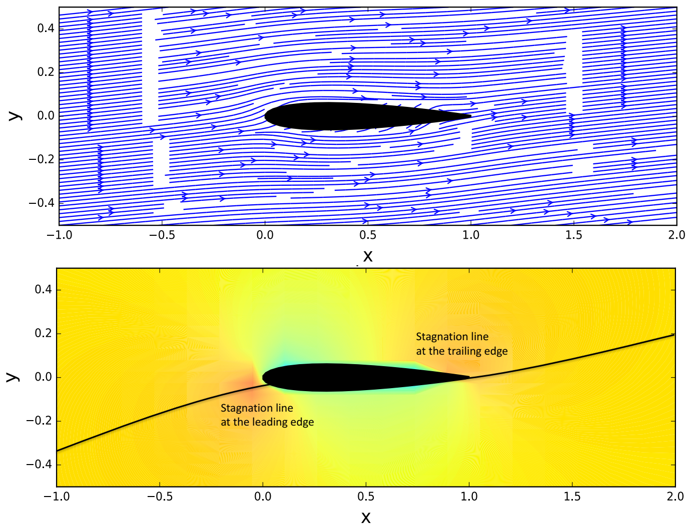

Figure 5: Streamlines around the airfoil (top), pressure contour around the airfoil (bottom)

Reference:

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