Aerodynamic Sound Generation due to Unsteady Laminar Flow past a Circular Cylinder Subjected to Rotary Motions

Ganta Naveen, Bikash Mahato and Yogesh G. Bhumkar*

Scientific Computing Laboratory, School of Mechanical Sciences, Indian Institute of Technology Bhubaneswar

1. Introduction and Objective

Flow over a circular cylinder is considered as one of the fundamental problems in fluid mechanics and it has numerous engineering applications such as flow over pantographs on high speed trains, airplane landing-gear, bridge pillars, sports equipment, transmission lines, heat exchangers, high rise buildings, automobile side mirror and many more. The unsteady nature of the flow field is responsible for structural vibrations and aerodynamic sound generation. Several flow control techniques have been introduced in many of the previous studies to control the structural vibrations and the aerodynamic sound. One such flow control technique is a cylinder subjected to rotary oscillations in a mean flow. In the present study, numerical analysis of aerodynamic sound fields radiated due to unsteady laminar flow past a circular cylinder subjected to rotary motions has been carried out using direct numerical simulations at a Reynolds number of $Re = 150$ and a Mach number of $M = 0.2$. Nature of aerodynamic sound fields has been studied for different forcing conditions.

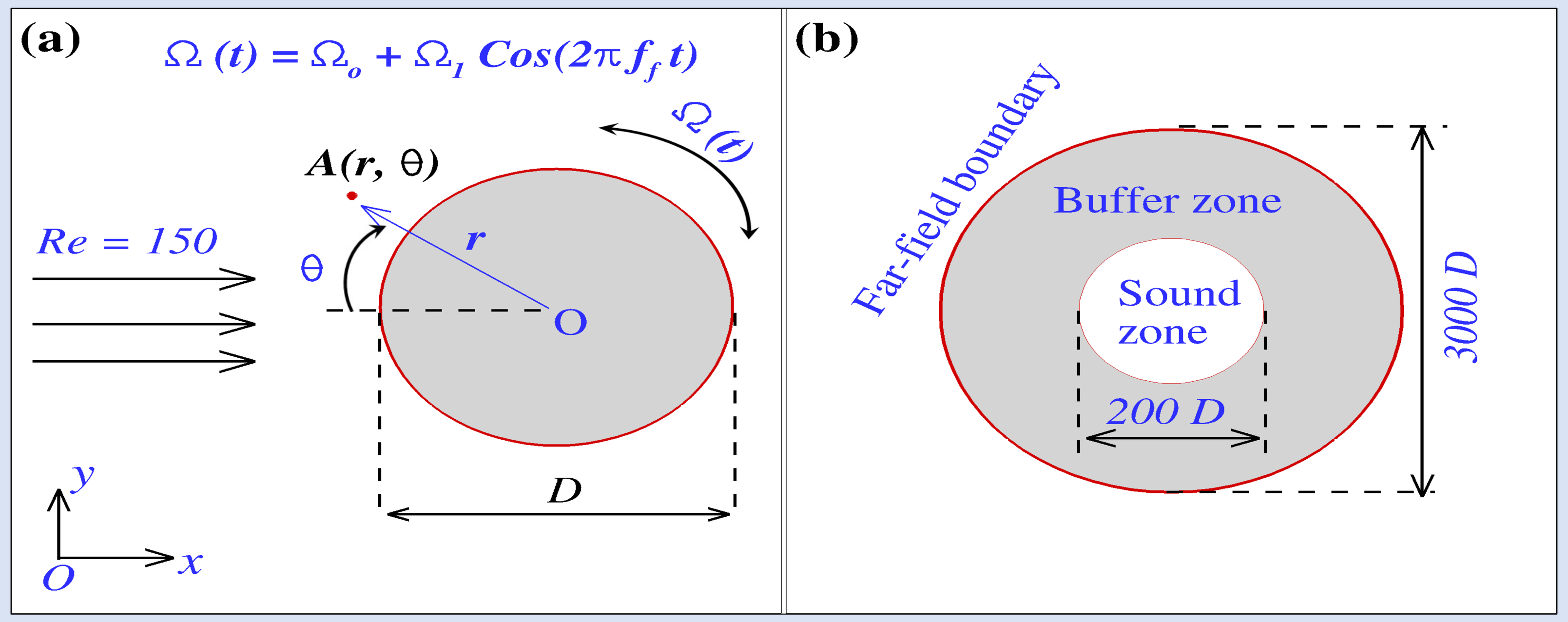


Figure 1: (a) Flow over a cylinder subjected to rotary motions, (b) Computational domain.

2. Forcing Parameters

- Non-dimensional tangential speed of the cylinder is prescribed as

$$V_t(t) = 2A_r + A_1 Cos(2\pi f_r St_o t^*)$$

Where, $A_1 = \Omega_1 D/2U_\infty$ is the maximum value of non-dimensional surface speed. The variables $f_r = f_f/f_o$, St_o and t^* account for forcing frequency-ratio, Strouhal number obtained for flow over a stationary cylinder at $Re = 150$ and the non-dimensional time, respectively. Here, Ω_1, D, U_∞ and f_o represent maximum angular velocity of rotary oscillation, diameter of the cylinder, free-stream velocity and the shedding frequency of a stationary cylinder at $Re = 150$, respectively.

- **Synchronous zone:** Vortex shedding frequency is same as forcing frequency.

$$A_1 = 2;\ \ 0 \le A_r \le 2;\ \ 0 \le f_r \le 2;$$

- **Non-Synchronous zone:** Otherwise

$$A_1 = 0.1;\ \ A_r = 0;\ \ 0.1 \le f_r \le 2;$$

3. Vortex Shedding Patterns

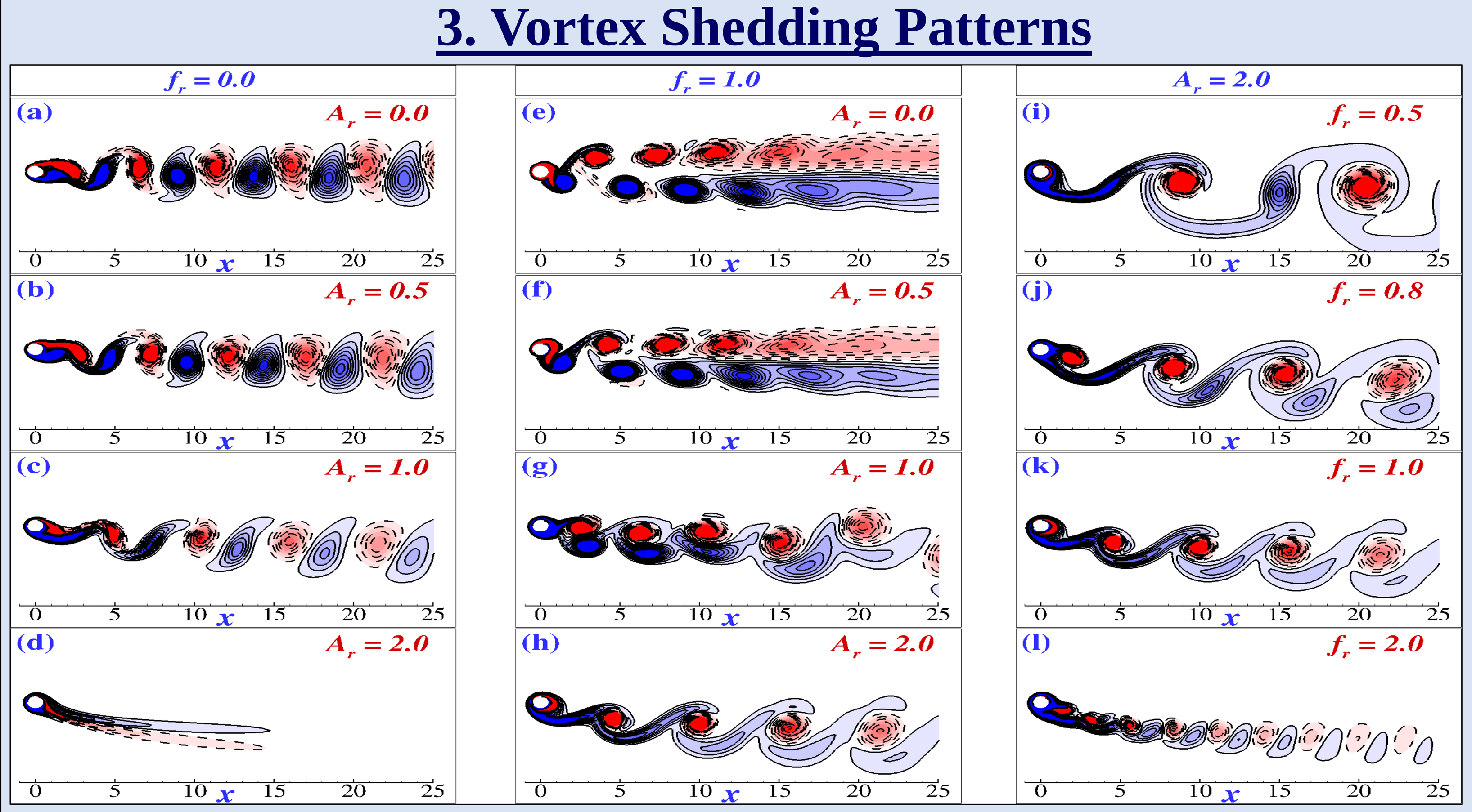


Figure 2: Variation of vortex shedding patterns for different forcing conditions.

- Vortex shedding has been completely vanished for $A_r = 2.0, f_r = 0.0$ case.
- Vortices in the wake are no longer symmetrically positioned along the horizontal axis due to imposed mean rotation rate, resulting in mean lift increment.
- As the system is in the synchronous zone for $f_r \neq 0.0$ cases, the vortex shedding frequency-ratio is same as forcing frequency-ratio.
- For $f_r = 1.0$ cases, the wake width has been reduced due to increase in mean rotation rate which further resulted in drag reduction.

4. Disturbance Pressure Fields

- Disturbance pressure ($p'(x, y, t)$) is evaluated from mean pressure ($p_m(x, y)$) and instantaneous pressure ($p(x, y, t)$) as given by: $p'(x, y, t) = p(x, y, t) - p_m(x, y)$

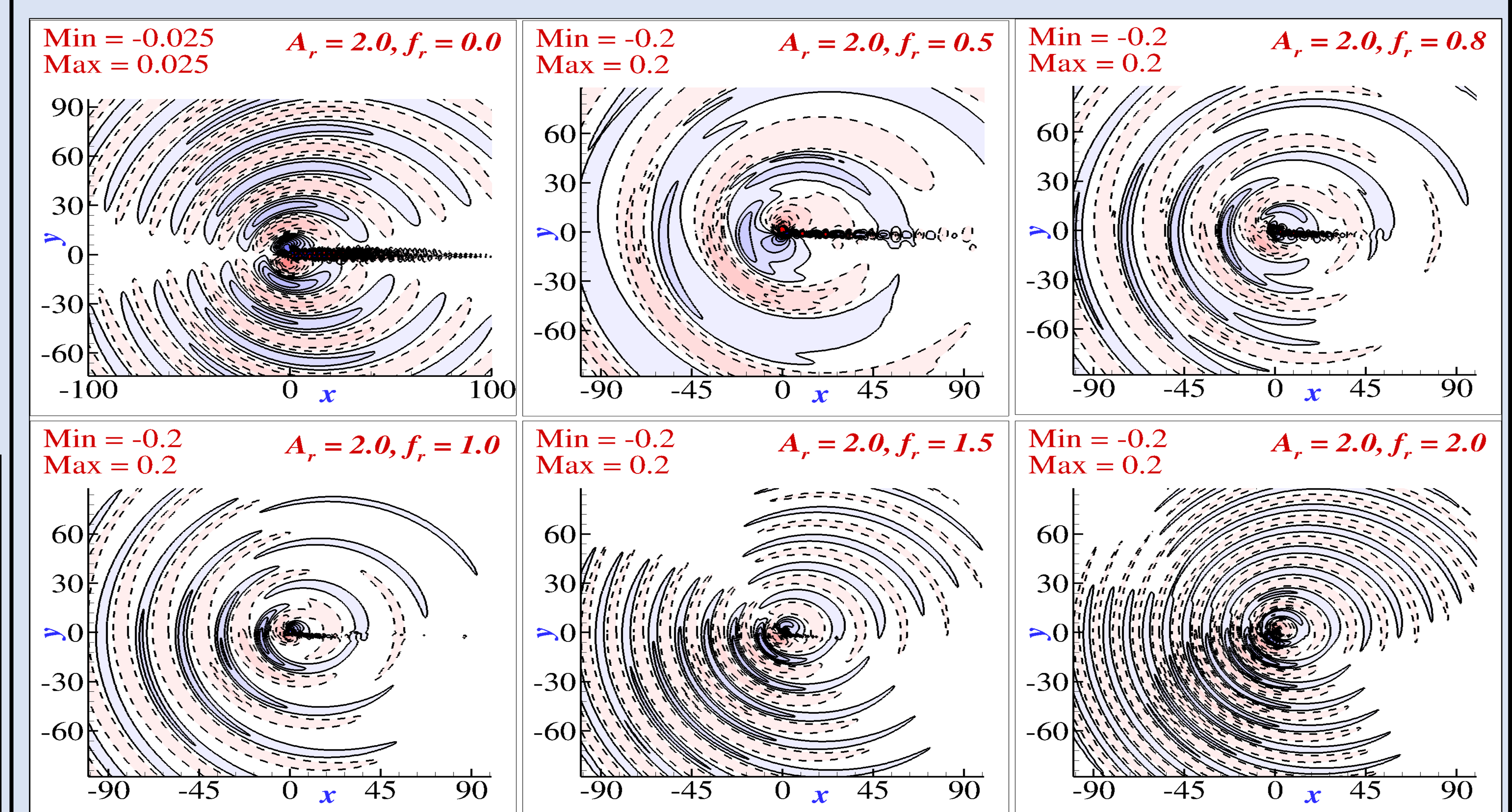


Figure 3: Variation of disturbance pressure fields for various values of f_r at $A_r = 2.0$.

- Positive and negative values of disturbance pressure are represented by solid and dashed lines, respectively.
- The wavelength of the generated disturbance pressure pulses decreases with increase in forcing frequency-ratio.

5. Nature of Far-Field Sound Pressure

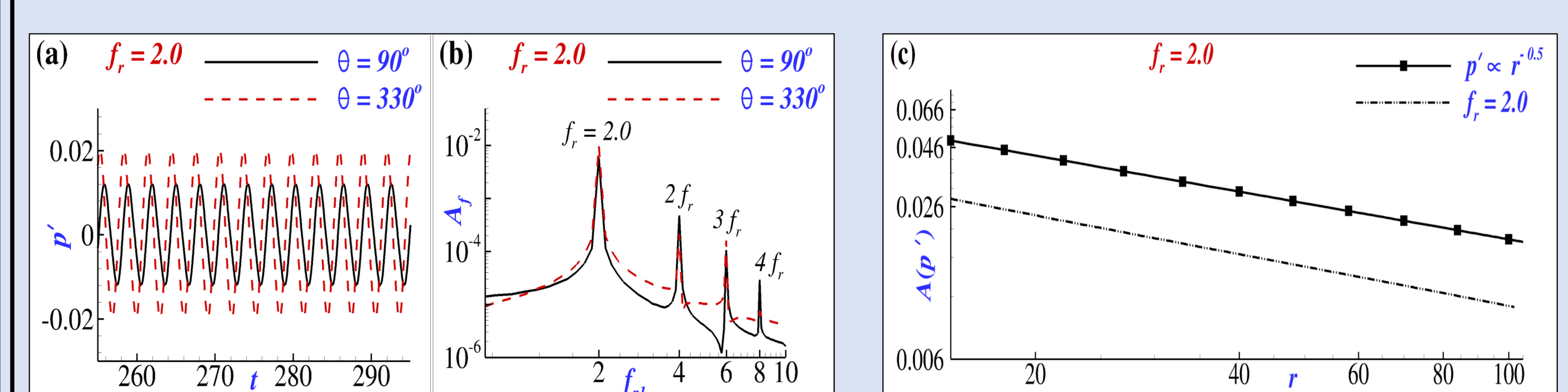
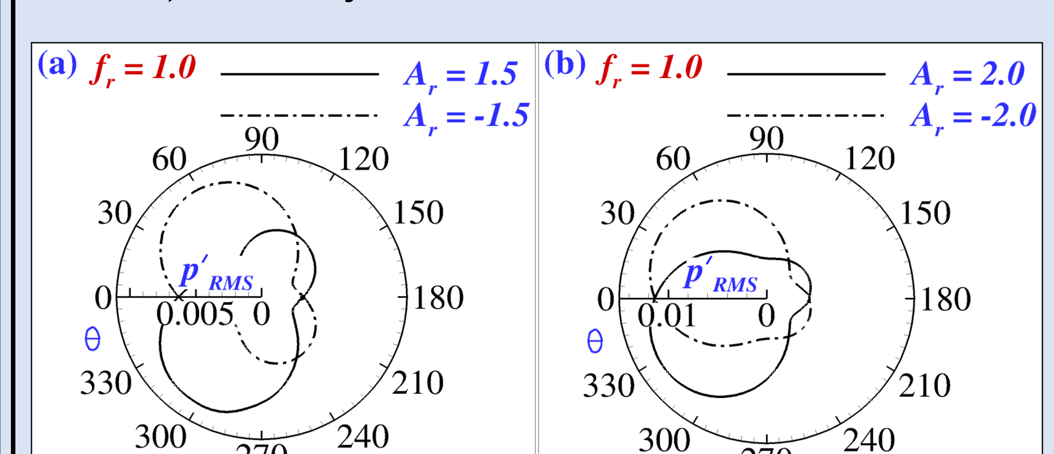


Figure 4: (a) and (b) represent the time-variation of far-field sound pressure and its frequency spectrum for $f_r = 2.0$ & $A_r = 2.0$, respectively. c) represents the decay of Fourier amplitudes of p' with radial distance (r).

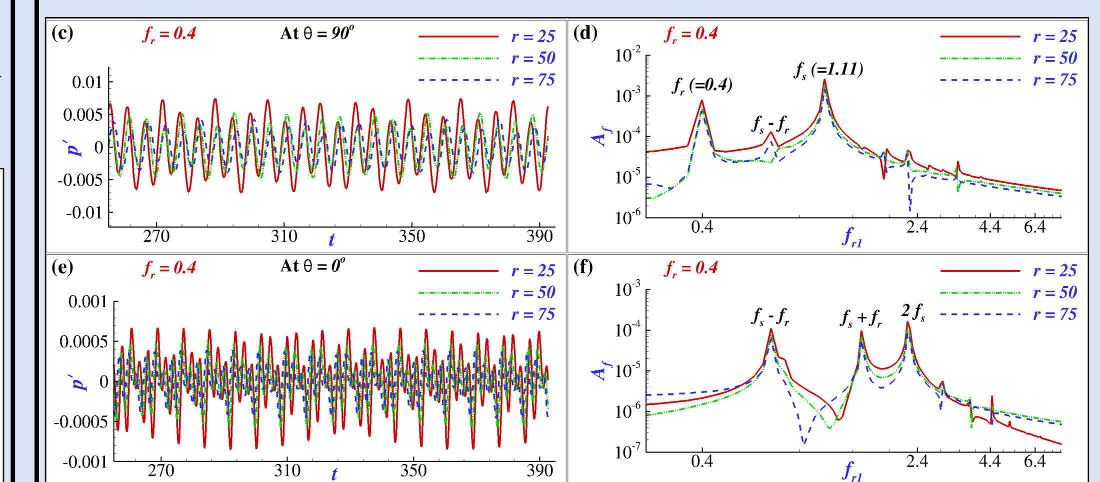
- The frequency spectrum of the disturbance pressure is governed by the applied forcing frequency.
- The decay of far-field disturbance pressure obeys the theoretical decay rate ($p' \propto r^{-0.5}$) of aerodynamic sound fields based on Curle's acoustic analogy (Curle 1955).



- Root mean square (RMS) values of time-varying disturbance pressure fields (p'_{RMS}) are evaluated.
- Directivity patterns are significantly altered due to imposed mean rotation rate.

Figure 5: Directivity patterns of radiated sound fields at $r = 75$.

6. Sound Fields in the Non-Synchronous Zone with $A_r = 0$



- Modulation patterns of sound waves have been observed.
- Generated sound fields are governed by the forcing frequency-ratio (f_r), the natural vortex shedding frequency-ratio of stationary cylinder (f_s) and their linear combinations.

Figure 6: Time-variation of far-field sound pressures and their frequency spectrum for $f_r = 0.4$ & $A_1 = 0.1$.

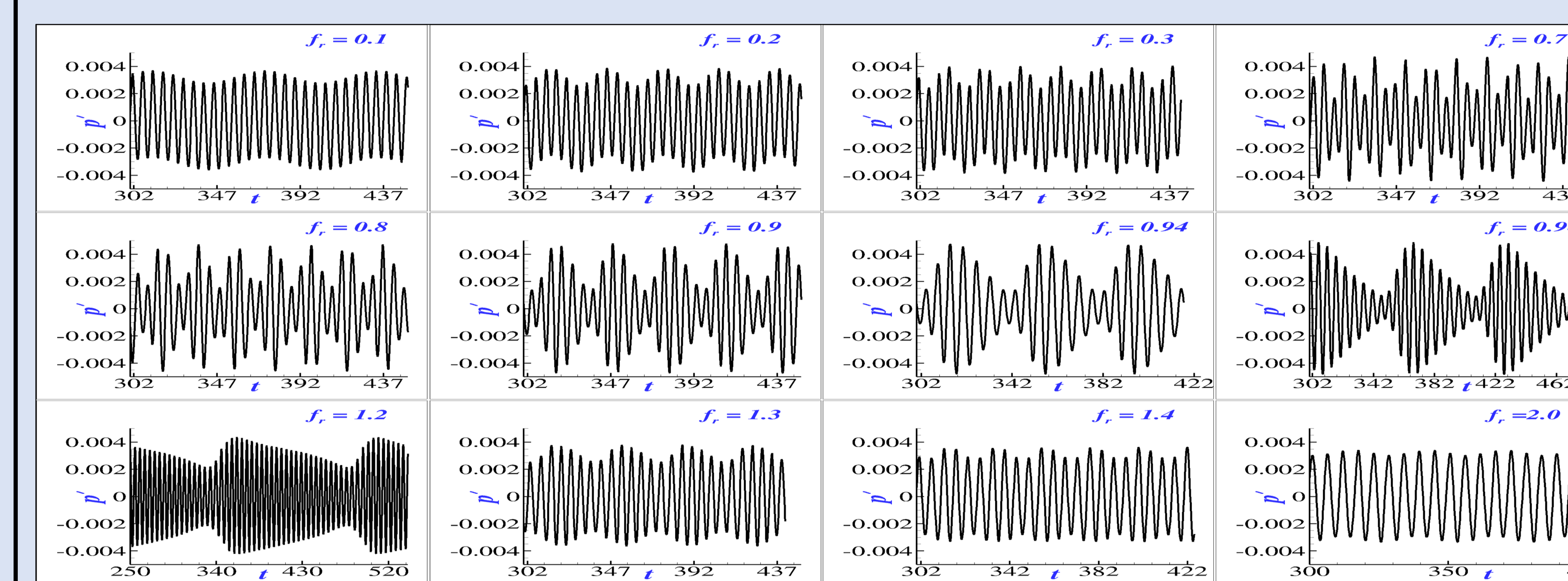


Figure 7: Modulation patterns of far-field sound pressure for different f_r values with $A_1 = 0.1$ at a location $(r, \theta) = (75, 90^o)$.

- Modulation patterns of the sound fields are significantly varied with change in f_r value.
- Sound beats are generated in the ranges $0.9 \le f_r \le 0.99$ & $1.2 \le f_r \le 1.4$.

7. Conclusions

- Direct simulations are carried out for the accurate prediction of aerodynamic sound fields generated due to flow over a cylinder performing rotary motions at $Re = 150$ & $M = 0.2$.
- In the synchronous zone, the frequency information of the radiated sound field is governed by the applied forcing frequency of rotary oscillation.
- Sound field directivity patterns are significantly altered due to mean rotation rates.
- Modulation of the sound waves and the aerodynamic sound beats are observed in the non-synchronous zone.

Acknowledgements

Some of the present numerical simulations are performed on a computational facility provided by the **late Dr. Sathyanarayana A.** who was one of my supervisors. I acknowledge him for his guidance, immense support and motivation.

References

- Curle, N. (1955). The influence of solid boundaries upon aerodynamic sound. *Proc. R. Soc. London*, Ser. A:231, 505–514 (1955).
- Ganta Naveen, Bikash Mahato, and Yogesh G. Bhumkar. "Modulation of sound waves for flow past a rotary oscillating cylinder in a non-synchronous region." ***Physics of Fluids*** 31.9 (2019): 096103.
- Ganta Naveen, Bikash Mahato, and Yogesh G. Bhumkar. "Prediction of the aerodynamic sound generated due to flow over a cylinder performing combined steady rotation and rotary oscillations." ***The Journal of the Acoustical Society of America*** 147.1 (2020): 325-336..

National Science Day
10th Research Scholars' Day 2020
IIT Bhubaneswar