A Study of Myoelastic-Aerodynamic Mechanism of Vocalization in Birds Based on Subject-Specific Computational Simulation of Fluid-Structure Interaction in Syrinx

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Abstract

The myoelastic-aerodynamic (MEAD) mechanism, which has been known to drive vocalization in humans, was recently observed in birds across a wide range of taxa. By using high-speed camera to film sound production in syrinx, Elemans et al. (2015) discovered that birds also have mucosal wave propagation on the surface of the lateral vibratory mass (LVM). This new discovery makes birds a very useful model for studying the fundamental mechanism of human vocalization and neural mechanism underlying vocal learning shared by some birds and human. The objective of the current study is to: (a) develop a first-principle based, fluid-structure interaction computational model which can accurately reproduce the vibration of LVM and sound signal; (b) validate the model against experimental measurements on rock pigeon models through subject-specific simulations; (c) use the model to study the detailed vibration pattern as well as the coupling mechanism of airflow and vibration in syrinx.

Keywords: Bird vocalization, fluid-structure interaction

1. Introduction

Recently, by using high-speed camera to film sound production in syrinx, Elemans et al. (2015) discovered that a wide range of taxa of birds might rely on the myoelastic-aerodynamic (MEAD) theory to produce sustained vibrations of their lateral vibration mass (LVM) which is the sound source of their voice. This is the same mechanism of human vocalization known for a long time. Briefly, when applying to human vocal fold, the MEAD theory states that the mucosal wave propagation on the vocal fold surface generates an alternative convergent/divergent glottal shape during the vibration which leads to a temporally-asymmetric aerodynamic force on vocal fold. This temporally-asymmetric aerodynamic force is the key mechanism for net energy transfer from the glottal flow to vocal fold (Titze and Alipour, 2006). In the experiments of Elemans et al. (2015), an alternative convergent-divergent shape of the airway between the two LVMs in birds' syrinx was also observed. However, different from human vocal fold which is only driven by the subglottal pressure and whose motion is dominantly in the lateral direction, the vibration of the bird LVM presents a more complex coupling mechanism and motion dynamics, such as that the vibration is driven by the combined effect of the air sac pressure and bronchial pressure, an additional tissue called the medial tympaniform membrane (MTM) vibrates together with the LVMs in a lower position, and a strong rotational motion presents during vibration. To elucidate the role and mechanism of these features in bird vocalization, a computational model which can faithfully model these features based on realistic conditions is necessary.

The objective of the current study is to: (a) develop a first-principle based, fluid-structure interaction computational model which can accurately reproduce the LVM vibration and sound signal under realistic bird vocalization conditions; (b) validate the model against the experimental measurements on rock pigeon models through subject-specific simulations; (c) use the model to study the detailed vibration pattern as well as the coupling mechanism of the airflow and vibration in the syrinx.

2. Computational method and simulation setup

2.1. Method

The computational solver is built upon our previous immersed-boundary-finite-element method based fluid-structure interaction solver (Zheng et al., 2010). The airflow is governed by the three-dimensional, unsteady, viscous, incompressible Navier–Stokes equations. The LVM dynamics is governed by the Navier equation with a linear stress-strain relationship. The fluid and structure solvers are explicitly coupled through a Lagrangian interface where airway and LVMs contact. Details regarding the numerical algorithm of the flow and solid solvers can be found in Zheng et al. (2010). A simplified one-dimensional wave equation is used to calculate the far-field acoustic pressure.

2.2. Simulation setup

The geometry of the model is reconstructed based on the thin-slice CT scan of pigeon syrinx. Before the dynamic simulation, a 1.0kPa air sac pressure is applied at the lateral surface of the LVM to deform it to the prephonatory position. According to the experiment, a sustained vibration can never be obtained without putting the LVM to the prephonatory position. For the dynamic simulation, a bronchial pressure and an atmosphere pressure are applied to drive the airflow through the tract. The LVM is assumed to be an isotropic material. The Young's modulus is estimated through the strain-stress relationship measured on the same pigeon model. Part of the LVM is constrained from movement due to its connection with bones. Other parts of the LVM is free to move. The acoustic pressure is calculated at the place 2.5cm away from the airway outlet

3. Results and discussion

The simulation is carried out until steady cycles are obtained. Table 1 compares the fundamental frequency, maximum opening size of the airway and sound pressure level at the place 2.5cm away from the airway outlet between the experiment and simulation. As can be seen, the numerical simulation matches well with the experiment.

Table 1 *Comparison of several key parameters between the numerical simulation and experiment (Elemans et al., 2015).*

	F0 (Hz)	Opening (mm)	SPL *(dB)*
Simulation	153	1.85	86
Experiment	140-160	1.8~2	~80

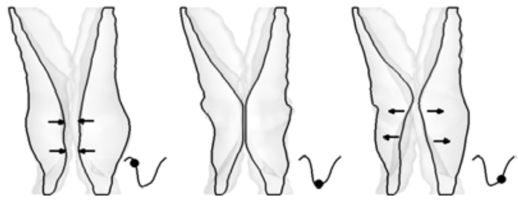

Figure 1. *The shape of the medial surface of the LVMs at three time instants during one vibration cycle. Each time instant is indicated by the black dot superimposed on the flow rate plot at the bottom right corner of each figure.*

Figure 1 shows the shape of the medial surface of the LVMs at three time instants during one vibration cycle corresponding to the closing, closed and opening LVMs. It clearly shows an alternative convergent-divergent vibration pattern of the LVMs. The LVMs close and open from the beneath, forming a divergent shape during the closing phase and a convergent shape during the opening phase. This is the similar vibration pattern with human vocal fold and the key mechanism of sustained energy transfer from the airflow to vocal folds.

Detailed vibration pattern, such as spatiotemporal variation of the displacement, POD analysis, node trajectory, will be analyzed in future to gain deep understanding of the vibratory dynamics of the LVMs. Aerodynamic pressure and its relationship with the vibration of LVMs will be analyzed and discussed to gain deep understanding of the interaction between the airflow and vibration.

4. Conclusion

The point that human phonation and bird vocalization both apply the MEAD theory is interesting for that it provides one more common phonation/vocalization mechanism between human and birds while the other similarity is that that both songbird and human learn vocalization from a tutor. Thus it provides us more confidence that the study of neural control during bird vocalization may be helpful in understanding the neural mechanism underlying human vocal learning.

5. References

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