directions, thus $W_\alpha < 0$. After t=1/2T, the MIV increases its strength as it moves to downstream. As the MIV travels to the trailing edge of upper surface, it generates a strong nose-down (negative) moment and results in a strong restoring impulse. At t=1/2T~3/4T, the deck section is forced to rotate to a negative angle as the flow time goes on, and the self-excited moment does positive work during this process. Then, the deck section moves back to the equilibrium position at t=3/4T~T, and $W_\alpha < 0$ is also because the deck rotates in the opposite direction of twist moment. In a sense, the MIV also plays an intermediary role for the energy transfer between the structure and the wind flow. For the deck section at +5° attack angle, as mentioned above, the same soft flutter state is reached both from the rest and from the large initial perturbation. It indicates that the MIV can be generated spontaneously or by the initial perturbation.

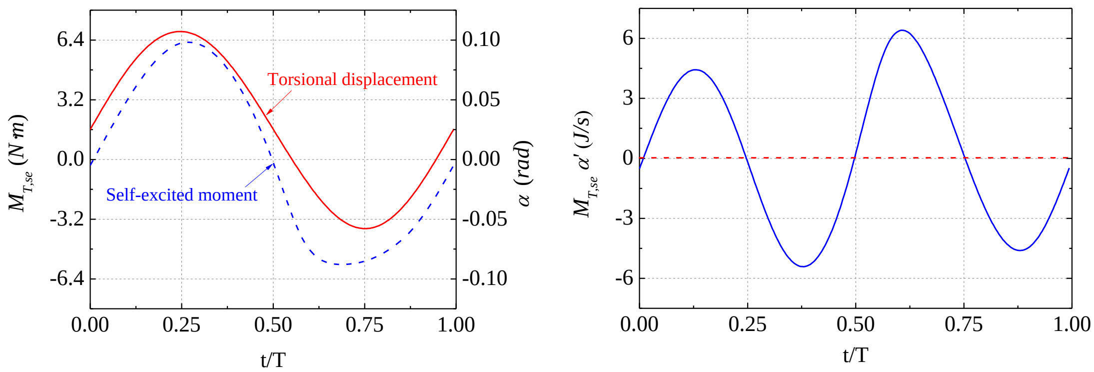

Fig. 13. Time history of aerodynamic moment, torsional displacement and associated aerodynamic power during one flutter cycle, 5° initial attack angle, U_0 = 12 *m/s*

Below the critical wind speed of soft flutter, the MIV caused by the initial perturbation is not strong enough to preserve the motion and the deck section is characterized by attenuated vibration. At the wind speed range of soft flutter, the MIV is strong enough when it moves along the surface of the deck section to generate large aerodynamic forces. The dynamic response of the deck section develops into steady state vibration due the strong nonlinearity of MIV-induced forces. As the wind speed increases, the strength of MIV becomes higher. After the critical wind speed of hard flutter, the energy absorbed from the wind flow through the MIV is more than that dissipated by structural damping, results in the occurrence of hard flutter.

7. CONCLUSIONS

Based on *ANSYS FLUENT*, a fluid-structure interaction (FSI) model has been developed to investigate the soft flutter characteristics of a bridge deck. The accuracy of present numerical model is verified by one thin plate section with theoretical solutions. The present numerical model successfully recaptures the soft flutter phenomenon of the bridge deck. With the increase of attack angle, the deck section becomes much blunter, and it is more prone to soft flutter. The soft flutter amplitude increases gradually with the wind speed until the hard flutter occurs.

The soft flutter of bridge deck is in a bending-torsion coupled mode, and the coupled vibration frequency linearly decreases with the increase of wind speed. The motion induced vortex (MIV) generated and shed periodically on the deck surface is the fundamental cause of the soft flutter of bridge deck. A stronger MIV is generated at the leading edge of deck surface, and the width of the MIV significantly decreases with the increase of torsional amplitude. So the MIV takes a longer time to travel to the tailing edge and shed from the deck surface, leading to a longer period for soft flutter. There must exist an aerodynamic energy balance for bridge deck during soft flutter, i.e., the fluid-structure system absorbs and dissipates energy in a certain vibration region so as to achieve the balance.

ACKNOWLEDGEMENTS

The research is jointly supported by the National Science Foundation of China (511780 86, 51478087).

REFERENCES

Amandolese, X., Michelin, S., Choquel, M., 2013. "Low speed flutter and limit cycle oscillations of a two-degree-of-freedom flat plate in a wind tunnel." *Journal of Fluids & Structures*, **43**(6):244-255.

Chen, Z., Yu, X., Yang, G., and Spencer Jr, B., 2005. "Wind-induced self-excited loads on bridges." J*ournal of Structural Engineering*, **131**(12), 1783-1793.

Cunningham, A.M., 2003. "Buzz, buffet, and LCO on military aircraft: the aeroelastician nightmare." In: *Proc. International Forum on Structural Dynamics and Aeroelasticity*, Amsterdam.

Fransos, D., and Bruno, L. (2006). "Determination of the aeroelastic transfer functions for streamlined bodies by means of a Navier–Stokes solver." *Mathematical and Computer Modelling*, **43**(5), 506-529.

Hassan, M., Gerber, A., and Omar, H., 2010. "Numerical estimation of fluidelastic instability in tube arrays." *Journal of Pressure Vessel Technology*, **132**(4), 041307.

Long, F., 2010. "Wind-resistant performance analysis and experimental investigation on long-span self-anchored suspension bridge." Dalian University of Technology, China. (in Chinese)

Majid, D.L.A.H.A., Basri, S.N., 2008. "LCO flutter of cantilevered woven glass/epoxy laminate in subsonic flow." *Acta Mechanica Sinica*, **24**(1):107-110.

Menter, F. R., 1994. "Two-equation eddy-viscosity turbulence models for engineering applications." *AIAA Journal*, **32**(8):1598-1605.

Nomura, T., Hughes, T.J.R. (1992). "An arbitrary Lagrangian-Eulerian finite rigid element method for interaction of fluid and a rigid body." *Computer Methods in Applied Mechanics & Engineering*, **95**(1): 115-138.

Scanlan, R. H., and Tomo, J., 1971. "Air foil and bridge deck flutter derivatives." *Journal of Engineering Mechanics*, **97**(6), 1717-1737.

Schneider, G., and Raw, M. (1987). "Control volume finite-element method for heat transfer and fluid flow using colocated variables—1. computational procedure." *Numerical Heat Transfer, Part A Applications,* **11**(4), 363-390.

Tang, L., Bartels, R.E., Chen, P.C., et al., 2003. "Numerical investigation of transonic limit cycle oscillations of a two-dimensional supercritical wing." *J Fluid Struct*, **17**(1): 29-41.

Wang, B., Zha, G.C., 2011. "Detached-eddy simulation of transonic limit cycle oscillations using high order schemes." *Computers & Fluids*, **52**(52):58-68.

Xu, F.Y. (2005). "Identification of flutter derivatives and flutter analysis of bridge." Tongji University, China. (in Chinese)

Xu, F.Y., Chen, A.R., 2008. "3-D flutter analysis of Sutong bridge." *Engineering Mechanics*, **25**(8): 139-144. (in Chinese)

Xu, F. Y., Ying, X. Y., Zhang, Z. (2014). "Three-degree-of-freedom coupled numerical technique for extracting 18 aerodynamic derivatives of Bridge Decks." *Journal of Structural Engineering*, **140**(11).

Ying, X.Y., Xu, F.Y., Zhang, Z. (2012). "Numerical simulation and visualization of flow around rectangular bluff bodies." *Proc., BBAA 7 Int. Colloquium on Bluff Bodies Aerodynamics and Applications*, Shanghai, China.

Zhang, C.G., 2007. "Soft flutter and parameters identification of nonlinear self-excited aerodynamic force of bridge girder." Tongji University, China.

Zhang, Q. and Hisada, T. (2004). "Studies of the strong coupling and weak coupling methods in FSI analysis." *International Journal for Numerical Methods in Engineering*, **60**(12): 2013-2029.

Zhu, L., Gao, G., 2015. "Influential factors of soft flutter phenomenon for typical bridge deck sections."*Journal of Tongji University (Nautual Science)*, **43**(9): 1219-1294. (in Chinese)