ΕΘΝΙΚΟ
ΜΕΤΣΟΒΙΟ
ΠΟΛΥΤΕΧΝΕΙΟ
ΣΧΟΛΗ ΜΗΧΑΝΟΛΟΓΩΝ ΜΗΧΑΝΙΚΩΝ

Α.Π. : 41807
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ΚΟΣΜΗΤΟΡΑΣ

Προς τα Μέλη ΔΕΠ της
Σχολής Μηχ/γων
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<u>ΠΡΟΣΚΛΗΣΗ</u>

Σας προσκαλούμε στην παρουσίαση της Διδακτορικής Διατριβής του Υ.Δ. **κ. Καπέλλου Χρήστου ,** διπλωματούχου Μηχανολόγου Μηχανικού του ΕΜΠ , την οποία εκπόνησε στον Τομ έα **Ρε υστών**. Η παρουσίαση θα πραγματοποιηθεί τη *<u>Δευτέρα 7 Οκτωβρίου 2019</u>*, ώρα *15:00 το μεσημέρι στην αίθουσα Τηλεκπαίδευσης στο κτίριο της Κεντρικής Βιβλιοθήκης ΕΜΠ* - Πολυτεχνειούπολη Ζωγράφου. Ο ελληνικός τίτλος της Διδακτορικής Διατριβής είναι ο εξής :

«Η ΣΥΝΕΧΗΣ ΣΥΖΥΓΗΣ ΜΕΘΟΔΟΣ ΓΙΑ ΤΗΝ ΑΕΡΑΚΟΥΣΤΙΚΗ ΒΕΛΤΙΣΤΟΠΟΙΗΣΗ ΜΟΡΦΗΣ ΣΤΗΝ ΑΥΤΟΚΙΝΗΤΟΒΙΟΜΗΧΑΝΙΑ»

και ο Αγγλικός Τίτλος ως εξής:

«THE CONTINUOUS ADJOINT METHOD FOR AUTOMOTIVE AEROACOUSTIC SHAPE OPTIMIZATION»

Ο Κοσμήτορας της Σχολής

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The Continuous Adjoint Method for Automotive Aeroacoustic Shape Optimization

Η Συνεχής Συζυγής Μέθοδος για την Αεροακουστική Βελτιστοποίηση Μορφής στην Αυτοκινητοβιομηχανία

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PhD Thesis Abstract

The present doctoral thesis deals with the mathematical formulation, programming and verification of the continuous adjoint method to the constituent parts of an existing noise prediction chain for automotive aeroacoustics. The proposed method is applied to optimize a generic vehicle, the SAE body, in order to reduce wind noise in its interior.

When a car travels at high speeds, flow-induced noise is generated in the region near the side mirror and is radiated towards all directions, reaching also the side window. Its vibrational response to this acoustic load generates in turn sound waves that propagate into the cabin and are perceived by the passengers as noise. An existing aeroacoustic framework simulating these physical mechanisms consists of an Improved Delayed Detached Eddy Simulation (IDDES) of the Navier-Stokes equations to obtain the unsteady pressure distribution on the mirror, the Kirchhoff Integral method to compute the radiated acoustic pressure on the side window, the bending wave equation on the side window to compute its deflection and, finally, the wave equation in the interior to obtain the interior sound field.

The continuous adjoint method in this thesis is based on the aforementioned framework which is split in two domains; the exterior domain that includes the flow-induced noise generation and radiation to the window and the interior domain that includes the vibroacoustic model for window vibration and interior wave propagation. These systems are firstly examined separately and, then, coupled and the contintuous adjoint chain for vehicle aeroacoustic optimization is proposed.

Regarding the vibroacoustic model, the bending wave equation is solved on the car's side window, using as a source term the pressure load obtained by the exterior domain. The resulting window acceleration is then used as a boundary condition for the wave equation that is solved in the cabin to compute the interior sound field. The Sound Pressure Level at a point near the driver's ear is then defined as the objective function and the adjoint wave and bending wave equations are derived. These must be solved backwards in time and in the following order: the adjoint wave equation is solved first by considering a monopole source term at the location where the objective function is defined. The propagation of the adjoint interior pressure in the cabin is computed and used thereupon as a source term for the adjoint bending wave equation, solved at the window. The resulting adjoint deflection is then used in the expression of the sensitivity derivative term on the window. This term is used later to couple the interior and exterior domains and additional emphasis is laid upon its discretization. A hand-differentiated expression is proposed to ensure its accuracy. The developed method is verified against Finite Differences and, then, is applied to the cabin of the SAE body to minimize interior noise using synthetic pressure waves as a load on the window.

The continuous adjoint method for the flow-induced sound radiation with the Kirchhoff Integral is proposed where the differentiated Kirchhoff Integral is used to compute the boundary condition of the adjoint velocity on the noise radiating (Kirchhoff) surface and, then, the unsteady adjoint Navier-Stokes equations are solved backwards in time. It should be noted that the time window where the simulation is performed and the one over which the objective function is evaluated do not coincide. This is reflected on the adjoint boundary conditions along the body and the time integration of the sensitivity derivatives. Furthermore, to ensure the consistency of the continuous adjoint-based gradients, grid sensitivities are taken into account which gives rise to the adjoint grid displacement equations along with an additional term in the sensitivity derivatives expression. The proposed method is verified against Finite Differences on a 3D turbulent flow around a cylinder and, then, applied to the SAE body. Firstly, a sensitivity map analysis is conducted to investigate the influence the sensitivity derivative integration time window has on its computation but, also, to prove the importance of including the adjoint grid displacement equations. Finally, an optimization of the side mirror is performed, targeting at minimizing the radiated flow-induced sound at the vehicle's side window.

After the formulation and verification of the continuous adjoint method for the systems of equations in the interior and exterior domains, their coupling is presented. Through the solution of the adjoint aeroacoustic chain, the sensitivity of the interior acoustic pressure with respect to a normal displacement of the mirror is computed to indicate the way the mirror shape should change, in order to improve the aeroacoustic performance of the vehicle. The method is applied to compute the adjoint aeroacoustic sensitivity map on the side mirror of the generic SAE vehicle and successfully perform several optimization cycles. In addition, the impact that optimizing for each individual step of the noise prediction chain has on interior noise is investigated.

Finally, two approaches are proposed, in order to perform the aforementioned adjoint analysis, focusing however on a specific frequency range; the first approach uses an objective function which includes the Fourier Transform and is integrated over frequencies whereas the second one uses a signal processing filter that preserves only the necessary frequency components. The adjoint formulation, advantages and drawbacks of each approach are discussed. The adjoint aeroacoustic chain including the filtering process is finally used to compute sensitivity maps on the mirror for the frequency range 800Hz-4000Hz and also for each 1/3 Octave Band in this range.

Keywords: Computational Fluid Dynamics, Continuous Adjoint Methods, Shape Optimization, Computational Aeroacoustics, Vehicle Aeroacoustics

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