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FLUID-STRUCTURE-ACOUSTICS INTERACTION OF AGARD WING 445.6 IN TRANSONIC REGIME

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ABSTRACT

This paper focuses on the fluid-structure-acoustics coupling of Agard wing 445.6 at transonic speeds. Prior to investigate the effects of elastic wing to aeroacoustics characteristics, several cases are conducted to validate the wing model. The modal analysis, aerodynamic analysis and steady-state two-way FSI analysis are performed as validation cases. The natural frequencies and mode shapes of Agard wing 445.6 are obtained and validated. Then, aerodynamics characteristics of the steady-state flow domain is analyzed using k-ε *turbulence model. The steady-state two-way FSI analysis are performed by system coupling. Fluid and structural solvers are connected to each other in a system coupling in order to transfer data between them. The total deformation of the wing is obtained by steady-state two-way FSI with performing system coupling. Then, acoustics relation with time dependent FSI of wing model is investigated by Ffowcs Williams-Hawkings model. The computed sound pressure level (SPL) and frequency of wing are compared with those obtained findings from aeroacoustics analysis in which elastic effects are not included. It is observed that the findings has significant implications for understanding of how fluid-structure coupling affects aeroacoustics behavior of the wing. The study shows that the elastic wing decreases SPL compared to the rigid wing.*

INTRODUCTION

The fluid-structure-acoustics interaction (FSAI) is a multidisciplinary field of study which is composed of three major physical fields. Fluid-structure coupling is the field of study that concerns with the interaction between fluid and structure parts. The applied aerodynamic forces cause to deformation on the structure which makes studies on this field very crucial. Agard wing 445.6 is a benchmark model that has been used by many researchers for the purpose of comparison and validations of aeroelastic studies. Several investigations are performed to explore FSI problems of Agard wing 445.6 model. Silva and de Morais [Silva and de Morais, 2016] carried out a FSI simulation to analyze aeroelastic characteristics of Agard wing 445.6. Sümer et al. [Sümer, Akgün and Tuncer, 2005] performed a loosely coupled FSI for analyzing static aeroelastic behavior of Agard wing 445.6 model. Similarly, Cai et al. [Cai, Liu, Tsai and Wong, 2000] studied FSI to perform the static

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aeroelastic characteristics of Agard wing 445.6. The Euler and Navier-Stokes computations are also compared in their study.

Acoustics of fluid-structure coupling concerns with the productions and absorption of noise and vibration by fluid flow [Howe, 1998]. A wing aeroacoustics is effected by the deformation of the structure since the aerodynamic sound is related with fluid-structure-interaction [Kaviani and Nejat, 2005]. The aeroacoustic noise pollution has an important issue that needs to be investigated. There are few studies in literature that investigated the effects of elastic structure on aeroacoustic characteristics up to now. Kaviani and Nejat [Kaviani and Nejat, 2005] investigated the aeroelasticity effects on aeroacoustics of Horizontal Axis Wind Turbines. In their study, it is conluded that power amount and noise level generated by flexible blades are less than those generated by the rigid blades. The other study that investigates the aerodynamic noise of large horizontal axis wind turbines experienced fluid-structure interaction is conducted by Kim et al [Kim, Lee, Son, Lee and Lee, 2012]. The result shows broadband noise decreased in elastic blades. The acoustic field resulting from the FSI is analyzed both numerically and experimentally by Schafer et al. [Schafer, Muller, Uffinger, Becker, Grabinger and Kaltenbacher, 2010]. Springer et al. [Springer, Scheit and Becker, 2017] performed a numerical flow computation with coupled aeroacoustic and vibroacoustic simulation. Valasek and Svacek [Valasek and Svacek, 2018] presented a mathematical description of the FSAI with low Mach numbers. In this study, the aeroacoustics characteristics of elastic wing is investigated and compared those with rigid wing in order to observe the effects of presence of FSI to acoustics behavior.

METHOD

In this study, Agard wing 445.6 is taken as a comparison and validation model which is based on NACA 65A004 airfoil. This wing model is tested by Yates [Yates, 1987] in NASA Langley Research Center at subsonic and transonic speeds. The geometrical parameters of wing model is given Table 1.

Table 1: Geometrical properties of Agard wing 445.6.

Semi-span length	0.762 m
Root chord	0.559 m
Tip chord	0.356 m
Taper ratio, λ	0.66
Sweep angle, Λ	45°

The material used for the wing model is laminated mahogany. In literature, there are two set of types of laminated mahogany which are very similar to each other. In this study, "weakened model 3" of this material, whose properties are listed in Table 2, is considered.

Table 2: Material properties of weakened model 3.

Material Property	Value
ρ	381.98 kg/m^3
E_{11}	3.1511 GPa
E_{22}	0.4162 GPa
E_{33}	0.4162 GPa
ν_{12}	0.31
ν_{13}	0.31
ν_{23}	0.31
G_{12}	0.4392 GPa
G_{13}	0.4392 GPa
G_{23}	0.4392 GPa

FSI is a field of study that investigates the interactions between fluid and structure. Aerodynamic force may generates additional stress and strain on a structure and causes a deformation on it. The severity of the deformation on structure may changed depending on fluid and solid characteristics such as pressure, velocity and material properties. There are two typical types of FSI problems, one-way and two-way FSI. In one-way FSI problems, fluid flow causes to deformation on structure due to pressure forces and there is no feedback from structure to fluid flow. However, in two-way FSI problems, there is an interaction between fluid flow and solid that affects each other. If the deformation on the structure is ignorable, then the structure probably will not affect the fluid flow. It is expected to observe valuable deformation on structure to experience effects on fluid flow's behavior. However, change in pressure waves in fluid may be experienced due to ignorable deformations if variation in time are fast. In case deformations are very large, then the deformations will effect the velocity and pressure values of flow as a return. The pressure waves resulted from structural deformations causes to radiation of sound consequently. There are too many methods to investigate FSI problems. Figure 1 illustrates the two-way FSI procedure. This procedure continues data transfering between two components until the convergence is achieved.

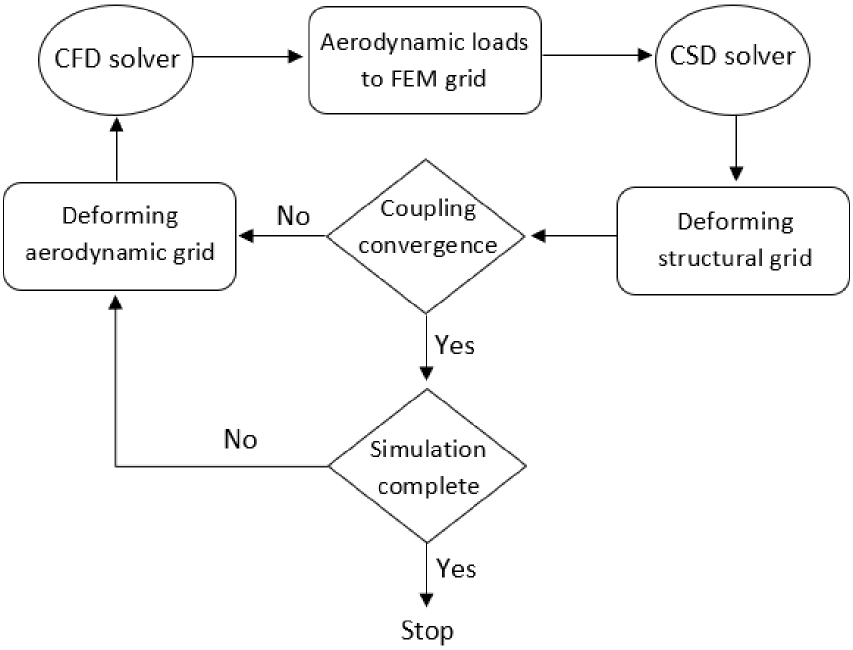


Figure 1: Schematic represantation of two-way system coupling simulation.

FSIA is a multidisciplinary field that investigated the effects of FSI to acoustics. The Ffowcs-William and Hawkings (FW-H) is utilized for aeroacoustic computation of the analysis. The FW-H equation, which is a form of Lighthill acoustic analogy, gives a standard approach for sound computation.

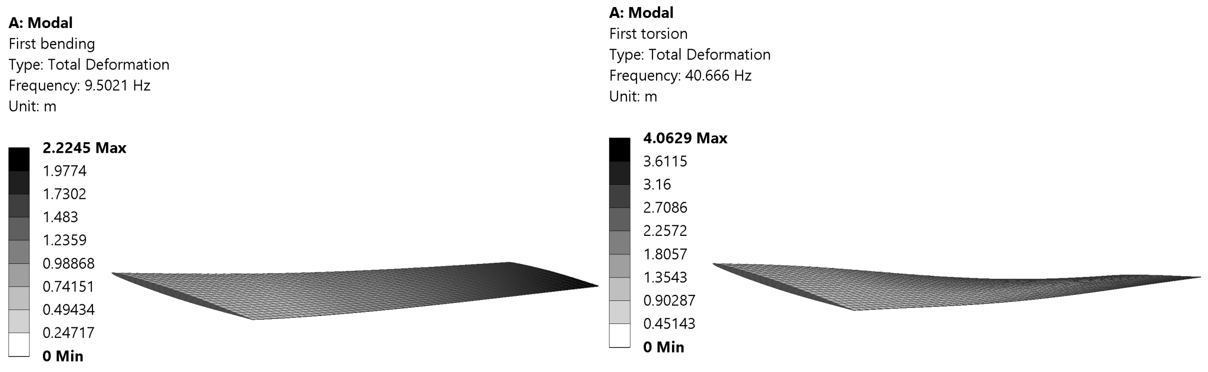
In this study, ANSYS software which is a commercial engineering tool, is utilized in order to analyze the all considered fluid-structure coupling cases of Agard wing 445.6. The system coupling module in ANSYS software enables analyzing the interactions between the structural and fluid parts of the wing model. The fluid and structural solvers are connected to each other in a system coupling. This connection allows data transfer between two components. One transfers data from fluent solver to structural solver whilst other one transfers data from structural solver to fluent solver.

RESULTS AND DISCUSSION

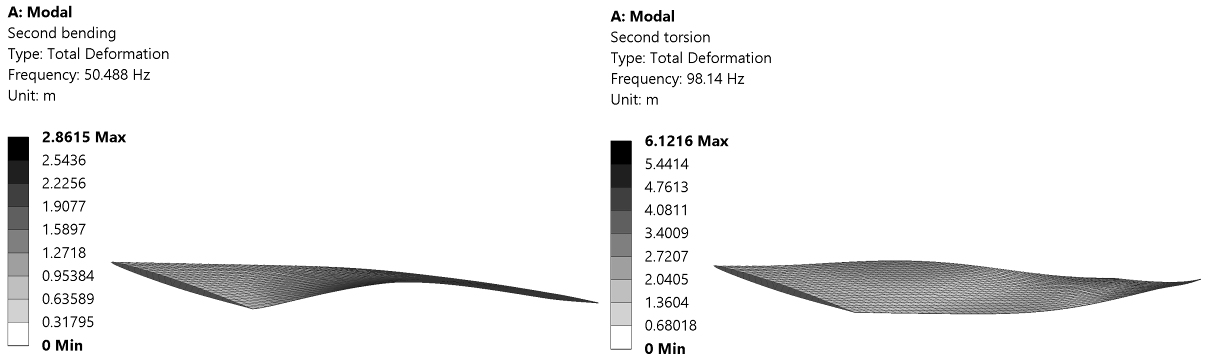
To the author's knowledge, there is no study on FSAI analysis of Agard wing 445.6 in literature. Therefore, several validation cases are performed separately which are modal analysis, fluent analysis and steady-state two-way FSI analysis of Agard wing 445.6. Firstly, modal analysis is conducted by using material properties of weakened model 3 of laminated mahogany. The model includes the 8469 nodes and 1200 elements. First four natural frequencies are obtained and compared with exact test model [Yates, 1987] in Table 3. The corresponding mode shapes of wing 445.6 are illustrated in Figure 2.

Table 3: Natural frequencies of wing model.

Natural Frequency (Hz)			
Mode Number #	**Present Study**	**Yates [1987]**	**Error (%)**
1	9.5	9.6	1.04
2	40.7	38.1	6.38
3	50.5	50.7	0.39
4	98.1	98.5	0.41



(a) First bending mode. (b) First torsion mode.



(c) Second bending mode. (d) Second torsion mode.

Figure 2: Mode shapes of Agard wing 445.6.

As can be seen from Table 3 that the obtained natural frequencies are in a good agreement with those of value from the literature. It is observed that there is a little difference between values in the second mode, it is estimated by the author that the error may caused from the uncertainties of material of Agard wing 445.6 in the literature.

Aerodynamic characteristics of Agard wing 445.6 is also investigated as a validation case. The fluid flow is assumed as turbulent and k-ε model is utilized as turbulence model. The Mach number is assigned as 0.96 Mach with 0° angle of attack. The pressure coefficient is obtained for the flow condition that corresponds to a Reynolds number of $Re{=}4.51x10^5$. Figure 3 shows the comparison of steady-state pressure coefficient distribution of current study with literature [Beaubien, Nitzsche and Feszty, 2005]. Closer inspection to Figure 3 shows that the correlation between current results and reference study is satisfactory until 70% of the chord. From that point, a small distinction between results is observed. A possible explanation to this distinction may be the usage of different turbulence models between these studies.

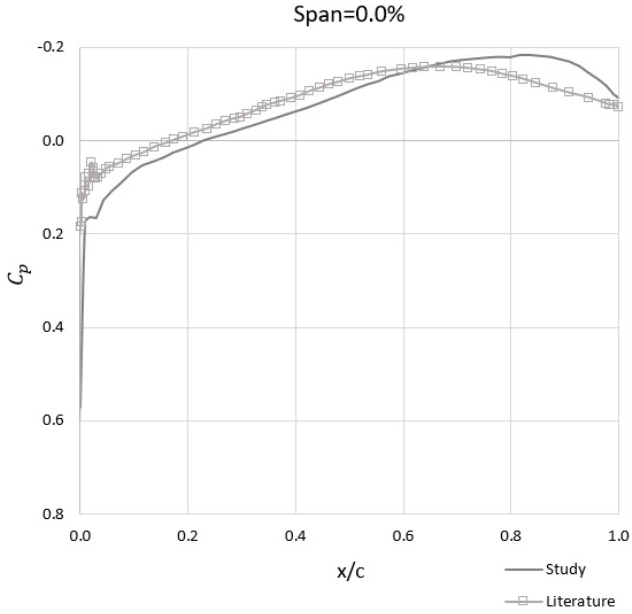


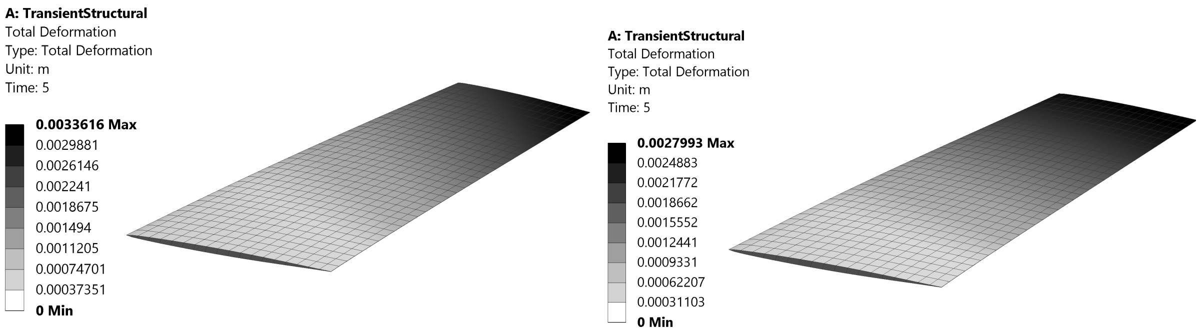
Figure 3: Comparison of steady-state pressure coefficient distribution.

The analysis of steady-state two way FSI is the another validation case. Structural and aerodynamics parts of the analysis are connected in ANSYS Workbench by system coupling component. Maximum 3 iterations are assigned for each system coupling step. The smoothing with spring/laplace/boundary layer is chosen as dynamic mesh method which is utilized for including changes in geometry. In this case, Mach number is assigned as 0.85 in the x direction with 5° angle of attack. The comparison of maximum deformation of current study with data from literature [Cai, Liu, Tsai and Wong, 2000] is given in Table 4.

Table 4: Comparison of the maximum deformation of wing model.

	Current study	Cai [2000]	Error (%)
Maximum deformation, mm	63.42	64.1	1.0

Table 4 indicates a good agreement between findings. The maximum deformation of Agard wing 445.6 is found as $63.42\ mm$ with the error 1%. After completing validation studies, the two-way time dependent FSAI simulation of wing model is performed with URANS methodology. In order to compare acoustics characteristics of fluent and FSAI analysis, the inputs of this analysis are taken as same as those of fluent analysis. As in the aerodynamic analysis part, k-ε turbulence model is utilized. The time step and end time for system coupling are taken as $5x10^{-2}\ s$ and $10\ s$, respectively. Maximum 3 iterations are assigned for each system coupling step. The analysis is performed at 0.96 Mach with 0 degree angle of attack. In this case, structural deformation and acoustics characteristics of wing model are analyzed in detail. The total deformation over the wing at 0.5 s for 0° and 10° angle of attack values are shown in Figure 4. Figure 5 shows the transient tip displacement of Agard wing 445.6 at 0° angle of attack that experienced FSI.



(a) Total deformation at 0 degree angle of attack. (b) Total deformation at 10 degree angle of attack.

Figure 4: Total deformation over the wing at different angle of attack values.

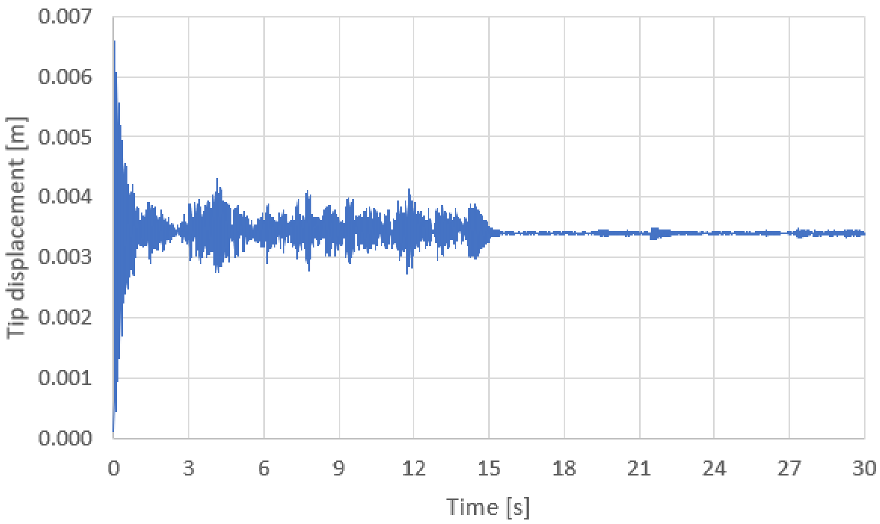
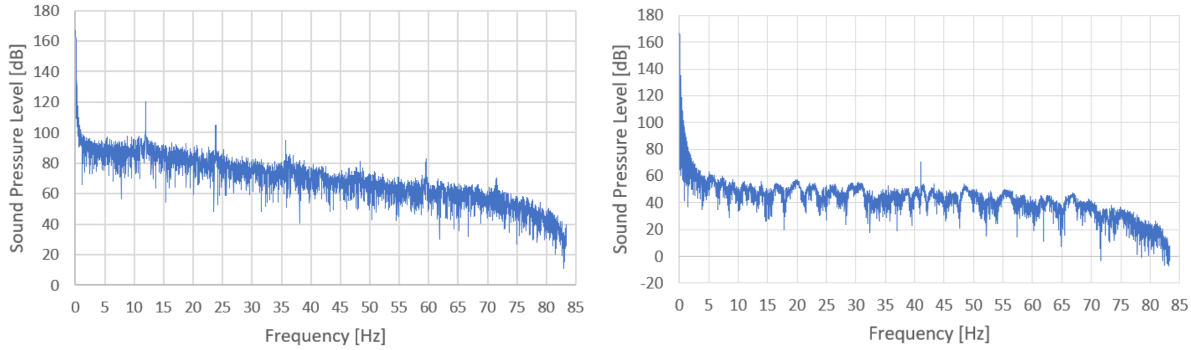
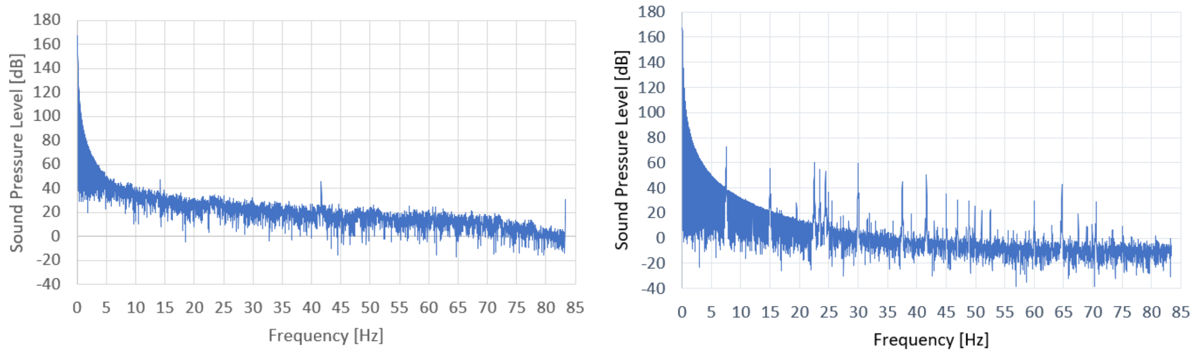


Figure 5: Tip displacement vs time.

The maximum deformation at 0° angle of attack is calculated as $0.0034\ m$ whilst the maximum deformation at 10° angle of attack is calculated as $0.0028\ m$. The standard earth gravity on the wing is introduced in the analyses, so it is considered that the reason behind the high displacement at the beginning may be caused by introducing standard earth gravity. Acoustic interaction with fluid-structure coupling is analyzed with the Ffowcs Williams-Hawkings model. To observe effects of FSI to acoustics, findings of FSAI are compared with acoustic solution of fluent analysis without considering structural effects. The computation of acoustics time signal at different angle of attack values are performed. The sound pressure level (SPL) of flexible and rigid wings from determined receivers are compared in Figure 6 at 0° and 5° angle of attack.



(a) SPL computation of fluent analysis at 0 degree. (b) SPL computation of FSIA analysis at 0 degree.



(c) SPL computation of fluent analysis at 5 degree. (d) SPL computation of FSIA analysis at 5 degree.

Figure 6: SPL plots of both analysis at different angle of attack values.

The computed frequency and sound pressure level of the wing model are compared with those obtained results from aeroacoustics analysis of wing model that experienced FSI. Figure 6 (a)-(c) shows the SPL plots from aeroacoustics analysis of wing model whilst Figure 6 (b)-(d) shows the SPL plots from FSAI analysis of wing model, respectively. It is expected that the presence of FSI affects the aeroacoustics characteristics of the wing. It can be deduced from the SPL plots computed from different receivers that the presence of FSI causes to decrease in sound pressure level at both $0°$ and $5°$ angle of attack values. Moreover, the frequency of aeroacoustics analysis without considering FSI has several peaks with respect to frequency of FSIA analysis. Closer inspection to the SPL plots of both fluent and FSIA analyses demonstrates that the elastic wing considerably reduces the SPL at both $0°$ and $5°$ angle of attack. This finding match those obtained in earlies studies. For example, the result of this study in agreement with findings from studies performed by [Kaviani and Nejat, 2005] and [Kim, Lee, Son, Lee and Lee, 2012]. It is also concluded in their studies that the elastic wing reduces the SPL compared to the rigid wing.

CONCLUSIONS

The aim of this paper is to analyze the FSAI of the Agard wing 445.6 with a multidisciplinary approach in detail. To validate the accuracy of model, several case studies are performed separately and findings are presented as quantitatively and qualitatively. The modal analysis, aerodynamic analysis and steady-state two-way FSI analysis are conducted and validated for wing model. For that purpose, natural frequencies and maximum deformation of the wing, steady-state pressure coefficient distribution over the wing are obtained and compared with literature. After completing several validation cases, fluid-structure-acoustics interaction of the wing is investigated using Ffowcs Williams-Hawkings model with time dependent two-way FSI. The total deformation over the wing at $0°$ and $10°$ angle of attack and transient tip deflection are obtained from this analysis. Then, SPL computations at both $0°$ and $5°$ angle of attack are performed and compared with SPL values from aeroacoustics analysis in which elastic effects are not included. The findings has significant implications for understanding of how fluid-structure coupling affects the aeroacoustics behavior of the wing. Based on the results of this study, it can be concluded that the presence of FSI considerably affects the aeroacoustics characteristics. The analyses show that the elastic wing reduces the SPL compared to the rigid wing. This study contributes to our understanding of relations between fluid-structure-acoustics interaction and effects of fluid-structure coupling on aeroacoustics behavior.

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