Journal of Aeronautics, Astronautics and Aviation, Vol. 56, No. 1S, pp. 267 – 277 (2024)
DOI: https://doi.org/10.6125/JoAAA.202403_56(1S).16

Comparative Study of Fluid-Structure Interaction Approaches for High Aspect Ratio Wing Applications

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ABSTRACT

In recent years, utilization of high aspect ratio (HAR) wings, particularly for high altitude long endurance (HALE) applications, has significantly increased. HAR wings play a crucial role in reducing the induced drag and also enhancing fuel efficiency. Nonetheless, HAR wings exhibit complex geometrical nonlinear behavior, posing challenges for optimal aircraft design. Traditionally, researchers have explored methods to analyze the geometrical nonlinearities through the fluid-structure interaction (FSI) analysis. However, most works for this area are predominantly focused on low aspect ratio wings, neglecting the complexities associated with HAR wings. Consequently, a critical research gap exists in understanding the unique challenges posed by HAR wings in the context of FSI analysis. This study addresses this gap by evaluating the effectiveness of FSI approaches (either using one-way or two-way) in the context of HAR wings using the ANSYS software. Comparative analyses between experimental and simulation results are conducted to verify the computational efficiency of both methods. The results have revealed that two-way FSI analysis closely approximates the experimental data, showing a maximum percentage error of 3.61% at an effective angle of attack of 1° and airspeed of 22.5 m/s. Nevertheless, it is important to note that two-way FSI analysis demands significantly more computational time compared to its one-way counterpart. Therefore, for straightforward cases involving HAR wing deformations, one-way FSI analysis is already sufficient to offer efficient and accurate results.

Keywords: Fluid-structure interaction, High aspect ratio wing, Geometrical nonlinear, ANSYS software

I. INTRODUCTION

In the past decade, there has been a surging demand for the development of flexible unmanned aerial vehicles (UAVs). Among various categories of UAVs, high altitude long endurance (HALE) aircraft has drawn considerable attention due to its ability for high operational endurance. HALE aircraft have been widely used for both military and civilian purposes. One of the HALE aircraft utilized by the military is the RQ-4 Global Hawk, manufactured by Northrop Grumman and operated by the US Navy and US Air Force. This HALE aircraft is designed for a wide range

Manuscript received, November 9, 2023, final revision, November 27, 2023
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of flight operations like weather forecast and intelligence, surveillance and reconnaissance (ISR). To stay aloft for a long period at a high altitude, it is necessary to design a wing that has a high lift-to-drag ratio and long endurance. In view of that, many researchers have proposed the use of a high aspect ratio (HAR) wing for the HALE aircraft. An example of a UAV design concept with a HAR wing is illustrated in Figure 1.

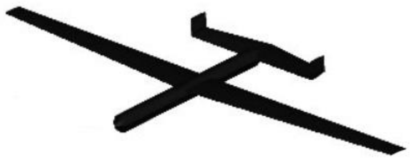


Figure 1 Generic concept of UAV with HAR wing [1]

A HAR wing is well-known for its high aerodynamic performance and capability to reduce induced drag [2]. However, the HAR wing is also prone to large deformation and structural flexibility, leading to geometrical nonlinear behavior [3-5]. Geometrical nonlinearity is induced by the constant movement and rotation of structural components along with large deflections [3]. The nonlinearity could be significantly observed in the large deformation of the HAR wing, which results in the curvature of the structure. This reflects the change in the dynamic behavior and aeroelastic response that leads to instabilities [6,7]. Hence, it is crucial to consider the geometrical nonlinearities in the design of HAR wings. The nonlinear approaches are demanded for the analysis as the linear approach cannot be employed due to its incapability to define the nonlinearity [8,9].

Several techniques have been applied for geometrical nonlinearity analysis as reported in the literature, which is either via analytical, experimental or numerical study. For the analytical approach, the modeling of the HAR wing might be done in three different ways: beam element, shell element or complex element [10]. Most previous conducted studies have chosen to idealize the HAR wing using beam components as this is more convenient. It should be noted as well that three types of beam models are often used, which can be displacement-based, strain-based and intrinsic beam models. In the meantime, there are also experimental studies that have been performed to validate the results of geometrical nonlinearities from numerical or analytical schemes through wind tunnel testing [11,12]. A few techniques have been used to measure the wing tip deflection inside the wind tunnel either by contact or non-contact method. In short, the contact method is where the measurement tool is placed on the wing model. An example of the contact method is using the mirror deflection technique, which has been implemented to measure the tip deflection of the HAR wing (AR-8.87) [11]. On the other hand, the non-contact method refers to the technique of measuring the tip deflection without any contact with the wing model. This method uses a videogrammetric model deformation (VMD) measurement technique to observe the behavior and deflection of the wing throughout the testing [11,12]. As an alternative to analytical and experimental approaches, the study of geometrical nonlinearity behavior can be done through numerical simulation. Numerical study is getting great attention these days because wind tunnel testing is time-consuming and costly. Indeed, for many years, the fluid-structure interaction (FSI) has commenced being one of the practical tools for aerospace design engineering.

FSI analysis has been used to study aerodynamic and structural nonlinearities. In general, there are two ways to perform FSI analysis, either through the monolithic or the partitioned approaches. For a monolithic approach, the data is transferred synchronously between the solvers. This is more computationally expensive compared to the partitioned approach, where the data exchange is not synchronized. In turn, this partitioned approach requires a coupling method (i.e. one-way or two-way) to cater for the unsynchronized data. The one-way FSI approach is more conservative and less computationally demanding compared to the two-way FSI method. In one-way FSI, only the effects of fluid flow on the structure, causing its resultant deformation, are considered and the effects of structural deformation on the fluid flow are not considered [13]. In contrast, the two-way FSI approach considers both effects. Hence, the utilization of the two-way FSI technique is more precise, particularly in the context of analyzing large deformation that is influenced by the fluid flow [13].

Three-dimensional FSI analysis has been applied in a study on flapping wing deformation (AR-1), with two-way coupling [14]. The numerical results are validated with the experimental data. Among others, findings from the study show that using lower time steps can improve the numerical accuracy of the results. The FSI analysis result also shows a good agreement with the experimental data at zero angle of attack and the difference between simulation results and experimental data at maximum angle of attack is just 7.6%. Furthermore, two-way coupling FSI analysis is also used to study the aeroelastic analysis of the flat plate composite wing and the HAR wing (AR-7) [15]. The analysis is done using the ANSYS fluent for flow analysis and the ANSYS mechanical for the finite element analysis (FEA). Similar work has also been conducted to investigate the aeroelastic analysis of a wing (AR-3) using ANSYS software [16]. In the study, dynamic meshing is used on the wing surface in the computational fluid dynamics (CFD) method for the FSI analysis. The aerodynamic forces have been solved by using Fluent as it is more reliable than the CFX solver for the coupling method. Besides that, another study has been done to study the behavior of the different materials on the wing deformation and aerodynamic performance. In this particular study, Eppler 423 airfoil cross-section shape is used for the wing (AR-6) [17]. One-way and two-way FSI analyses have been performed in this study using ANSYS solver. The findings indicate that the observation of wing deformation in the two-way FSI analysis is comparatively lower than that observed in the one-way FSI analysis. In addition, pressure loads from two-way FSI analysis that are applied to the structure reduce the effective loads that act on the wing, which results in reduced deformation for both materials. Moreover, a one-way FSI approach has been applied to study the wing deflection (AR-6) and the results are validated with experimental results [18]. The findings show that one-way FSI analysis tends to predict a higher wing deflection.

Based on the conducted extensive reviews, it appears that most of the previous works have been concentrated on low aspect ratio wings and also methods for studying wing deflection. In this sense, a gap exists in understanding the comparative effectiveness between one-way and two-way FSI analyses for the study of HAR wings. With this notion, the presented study in this paper aims to bridge this gap by investigating the competency of different FSI approaches for analysis of the HAR wing model.

II. SETUP AND METHODOLOGY

A comprehensive approach employing FSI analysis is adopted in this study to investigate the deformation behaviors of the HAR wings. The analysis is conducted utilizing the ANSYS software that is integrated with the CFD and FEA techniques. The flow process of FSI analysis is illustrated in Figure 2.

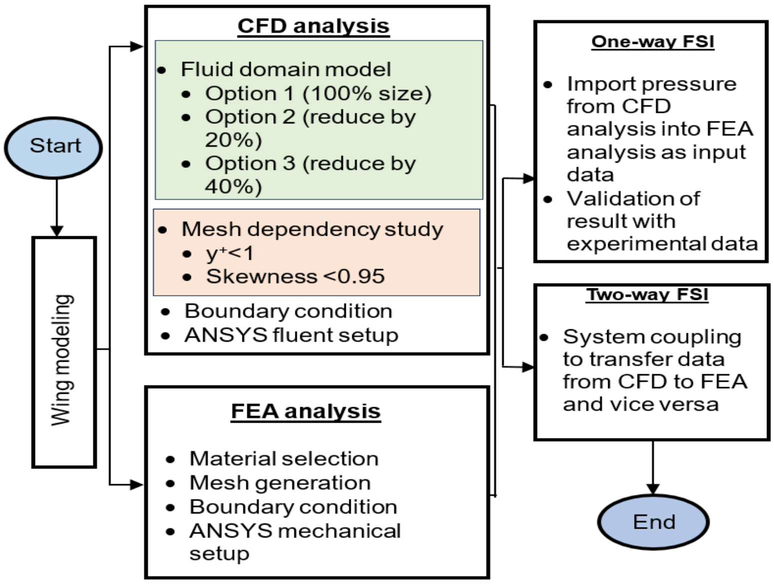


Figure 2 Work process for FSI analysis in this study

In short, the first step of this analysis involves the modeling process of the HAR wing structure, including its geometrical details and material properties. This step ensures the realistic representation of the wing's physical characteristics within the computational domain. Once the model has been constructed, CFD analysis is performed to understand aerodynamic forces acting on the wing under various conditions such as different airspeeds and effective angles of attack. The next process involves FEA analysis, which is an essential method to comprehend the structural behavior of the wing. Lastly, the final and pivotal phase of this study involves the FSI simulations that integrate both findings from CFD and FEA analyses.

2.1 Wing Modeling

The HAR wing model used in this study has a symmetrical airfoil NACA 0012 as its cross-sectional shape and aspect ratio of 16. This airfoil was chosen to simplify the analysis of the HAR wing. The wing geometry is first created in ANSYS design modeler while the coordinates for the airfoil design are imported from Microsoft Excel. These coordinates are then linked to form the curve of the airfoil and are extruded according to the wingspan length. It should be noted that the dimensions of this HAR wing are based on previous work in [19]. The summary of the specifications for the wing's model is tabulated in Table 1.

Table 1 Wing model's specifications

Parameter	Value
Number of ribs	16
Wingspan length (m)	0.8
Chord length (m)	0.05
Spar width (m)	0.025
Distance between rib (m)	0.05
Rib thickness (m)	0.009

As can be seen in Figure 3, the HAR wing consists of three main components: spar, rib and fairing. In the figure, Ls is the wingspan length whereas Lc is the chord length. The spar is the crucial component in the HAR wing model, which needs to have adequate flexibility and durability to withstand intense resonance vibrations such as flutter [20]. Because of this, the spar component is modeled with spring steel material. As for ribs, Acrylonitrile Butadiene Styrene (ABS) material has been chosen. Furthermore, the fairings component is assigned with styrofoam material. It should be noted these assigned materials are tailored to the wing model used in the wind tunnel testing in [19].

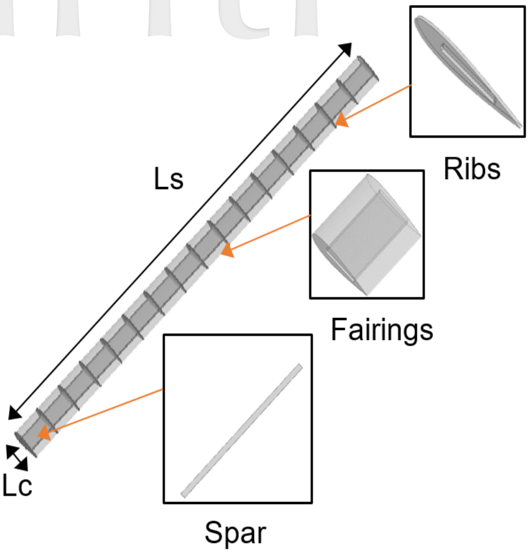


Figure 3 HAR wing model

2.2 Computational Fluid Dynamics

In this study, ANSYS Fluent software is employed for CFD analysis of the HAR wing model. It should be noted that CFD simulation analysis is widely accepted and used in various engineering research including in the study of aerodynamic noise generation [21] and aerodynamic performance [22,23]. For this research study, the process begins with accurate fluid domain modeling and this is followed by generation of the optimized mesh. Boundary conditions have been carefully defined for accurate real-world representation to ensure reliable results.

In terms of the fluid domain model, the C-H domain is used to observe the flow behavior around the HAR wing as shown in Figure 4. This selection is made based on its high accuracy and computational efficiency [24]. The discrete fluid domain surrounding the model is necessary to define the role of the structural model in the fluid environment. The fluid domain is allocated approximately 20 times the wing's chord length to ensure accurate results. Moreover, a Boolean subtraction operation is performed to eliminate the wing from the fluid domain to prevent any interference with the wing's surface. For this study, three domain size options are explored as shown in Figure 4. The first option has a domain length and height of approximately 20 times the chord length from the airfoil, ensuring optimal fluid flow results [24]. Domain size for the second option is reduced by 20% compared to the first option while the third option has a further reduced domain size by 40% as compared to the first option. This percentage reduction is chosen to analyze the impact of domain size on the result of the HAR wing's deformation.

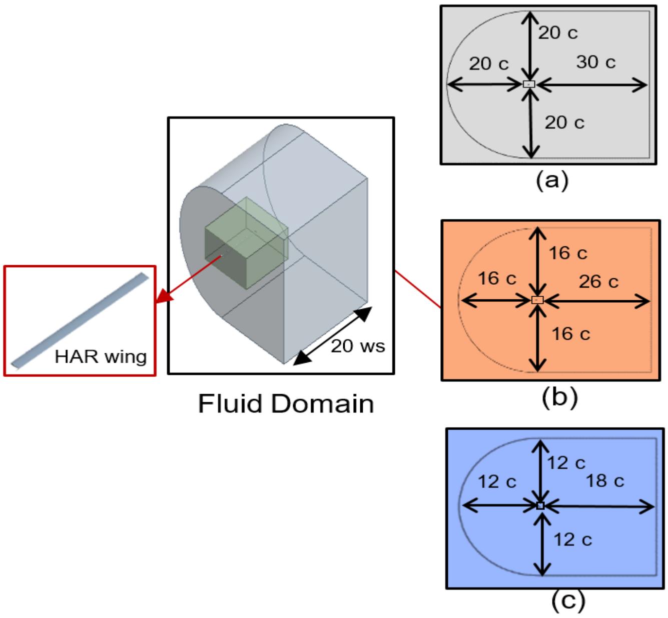


Figure 4 Fluid domain size with (a) option 1 (100% size), (b) option 2 (reduced by 20%), (c) option 3 (reduced by 40%)

ANSYS meshing software is employed to generate an unstructured mesh for the HAR wing model in this study. The unstructured mesh needs less time to compute while still maintaining its accuracy [25]. The HAR wing meshes in three different ways: coarse, base and fine. To achieve an efficient mesh, different mesh edge sizing and inflation layers are generated during the modeling and simulation processes. In order to obtain an accurate result, it is critical to analyze the wall y+ value. In the viscous sub-layer area, where viscous stress dominates the wall shear, the wall y+ value is determined to be less than one. The mesh creation of the wing is shown in Figure 5.

The subsequent phases in CFD analysis necessitate a selection of appropriate turbulence models for the resolution of the boundary layer. A few types of turbulence models are available: Spalart-Allmaras, Shear Stress

Transport (SST), k-omega SST and standard k-epsilon. For this work, the k-omega SST turbulence model is selected. An advantage of the k-omega SST model is that it is near the wall treatment, where the model is more accurate in resolving boundary layers, particularly when it is subjected to adverse pressure gradients [25].

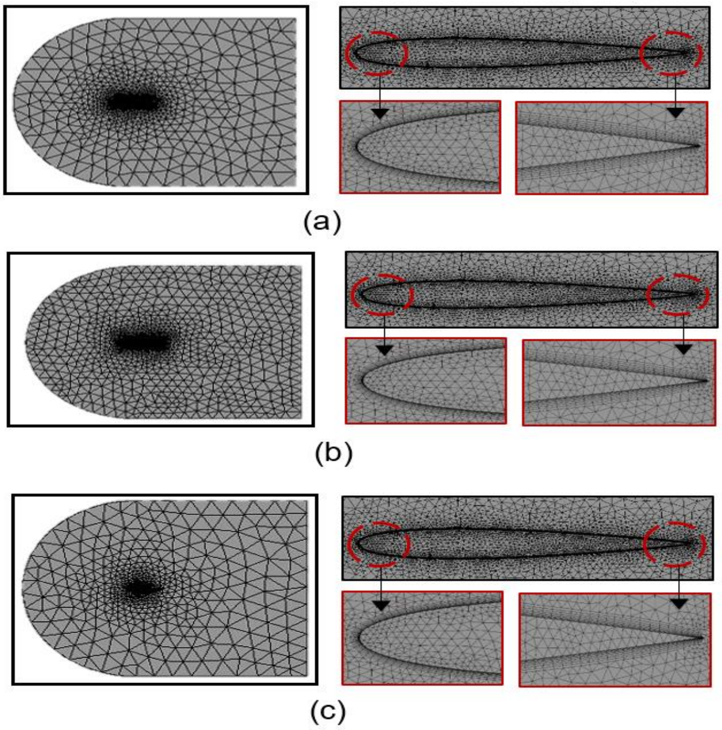


Figure 5 Meshing of the HAR wing model: (a) coarse mesh, (b) base mesh, (c) fine mesh

Moreover, the boundary conditions for the model are determined. In general, the boundary conditions consist of inlet, outlet and internal face boundaries in the domain model. For this study, at the inlet surface, the inlet velocity is set with various air speeds starting at 5 m/s. On the other hand, the output surface is designated as a pressure outlet with default gauge pressure values. The domain wall that is attached to the HAR wing is assigned as a symmetrical wall in order to simulate zero-shear slip walls in viscous flows. A no-slip boundary condition is applied to the wing surface, assuming zero velocity at the wall.

For the simulation setup, the pressure-based solver combined with the coupled algorithm is employed as it has a faster and monotonic convergence rate. In essence, this algorithm concurrently solves continuity and momentum equations, where the continuity and momentum equations are independently solved. This method also enhances the robustness of the solution by insulating it against any error arising from the initial conditions, nonlinearity in physical models, thereby maintaining the stability of the iterative solution process. The unsteady and incompressible RANS equations are solved implicitly and segregated using a 3D finite-volume technique. A second-order accurate upwind discretization technique is applied for the convective and viscous elements of the RANS equations.

2.3 Finite Element Analysis

The FEA analysis of the HAR wing is performed by using ANSYS Mechanical software. Like CFD, the FEA simulation analysis has been well-accepted and applied in various engineering studies for analyzing the structure of satellites [26], smart composite plates [27] and wing box of an aircraft [28]. To conduct the FEA simulation analysis, several steps are undertaken. The process starts with defining the material properties of the HAR wing model. This ensures precise results in deformation. Following this, the HAR wing model is meshed and appropriate boundary conditions are determined. Once everything is completed, the simulation analysis can be performed.

In FEA analysis, the material selection and properties are crucial to define the behavior of the structural model. The material properties are defined in the engineering data of the ANSYS Mechanical software, which include density, Young's modulus and Poisson's ratio. The details of material properties for the HAR wing model in this study are presented in Table 2.

Mesh generation is an essential aspect of the model setup in numerical simulation and the setup component of the ANSYS Workbench is used to mesh the model. Mesh generation is vital because discretized elements contribute substantially to the accuracy of the results. For accurate results, a fine mesh is essential for the structural model as shown in Figure 6. For this study, the maximum skewness is 0.725. Meanwhile, for the FEA boundary conditions, the wing model is set up with the cantilever beam's condition. The root chord or root surface of the wing is applied with a fixed support as shown in Figure 7. In this analysis, the large deflection setting is selected to define the nonlinear behavior of the HAR wing. Next, external load pressure on the wing surface is applied, which is imported from the results of the conducted CFD analysis.

Table 2 Material properties of the HAR wing components

Wing component	Material	Properties	Value
Spar	Spring steel	Young Modulus, E_s	207 Gpa
		Density, ρ_s	7833.41 kgm^{-3}
		Poisson's Ratio, v_s	0.295
Rib	ABS	Young Modulus, E_r	13.9 Gpa
		Density, ρ_r	1264.83 kgm^{-3}
		Poisson's Ratio, v_r	0.35
Fairing	Styrofoam	Young Modulus, E_f	20 Mpa
		Density, ρ_f	127.68 kgm^{-3}
		Poisson's Ratio, v_f	0.22

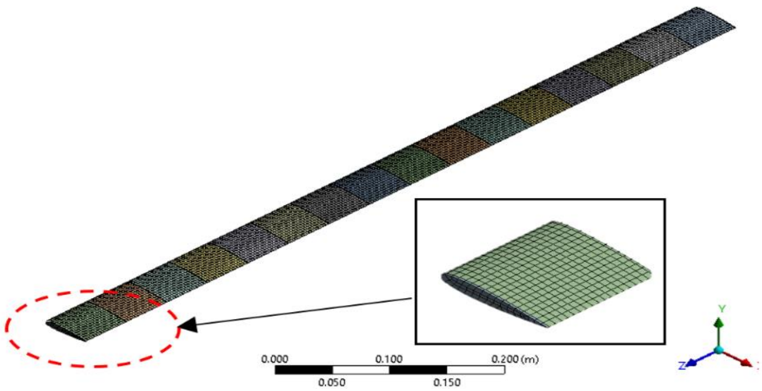


Figure 6 Structural mesh of the HAR wing model

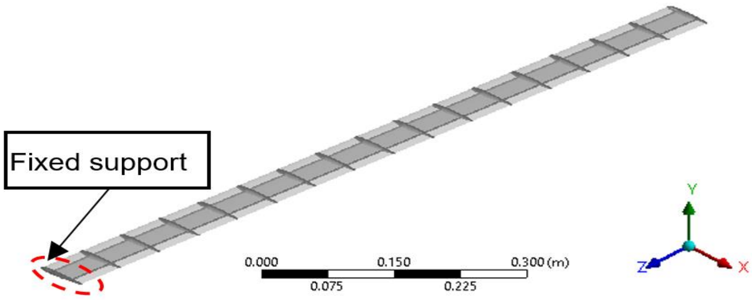


Figure 7 Boundary condition for HAR wing model

2.4 FSI Analysis

This study applies both one-way and two-way FSI analyses to investigate HAR wing deformation. One-way FSI analysis is initially employed to validate the simulated HAR wing deformation across the varying domain sizes against the published experimental data. After validation, a comparative analysis between one-way and two-way FSI approaches is conducted, assessing the effectiveness of the methods in comparison with the experimental results.

In this study, a thorough one-way FSI analysis has been done using ANSYS Fluent and ANSYS Mechanical software. The process includes importing the pressure data from ANSYS Fluent into ANSYS Mechanical, serving as an essential input for precisely calculating the deformation of the HAR wing as shown in Figure 8.

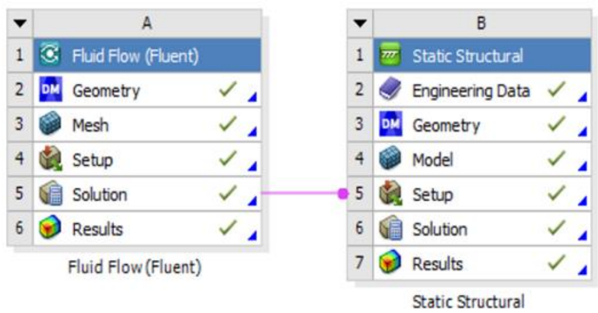


Figure 8 One-way FSI analysis settings

The simulation results are then validated against experimental data under various effective angles of attack. The detailed comparison of the simulated and experimental outcomes can help provide a comprehensive and precise assessment of the HAR wing's behavior, enhancing the depth and reliability of the current findings. On the other hand, a two-way FSI analysis is done to determine the deflection of the HAR wing under various effective angles of attack and air speeds. In this approach, the ANSYS Mechanical (providing FEA data) and Fluent (providing CFD data) have been integrated, requiring the implementation of a coupling system to aid the exchange of results. The FSI analysis requires the coupling system to transfer data from the fluid analysis to the finite element analysis. In the ANSYS software, the transferred data are simulated in the independent solvers and the results are generated. The system coupling in ANSYS, as indicated in Figure 9, manages the exchanged data transfer between the solvers and also coordinates both solvers. In two-way FSI, the data from Fluent is transported to Mechanical and vice versa until a solution has converged. For the setting of the analysis, duration control is set to the end time as 0.0075 s and the step size as 5e^{-05} s. This time step has been chosen as the analysis reaches the stability and convergence of the coupled simulation. In addition, it is also vital to check the mapping between the fluid and structure to be 100% under the coupled solution to avoid errors during the simulation.

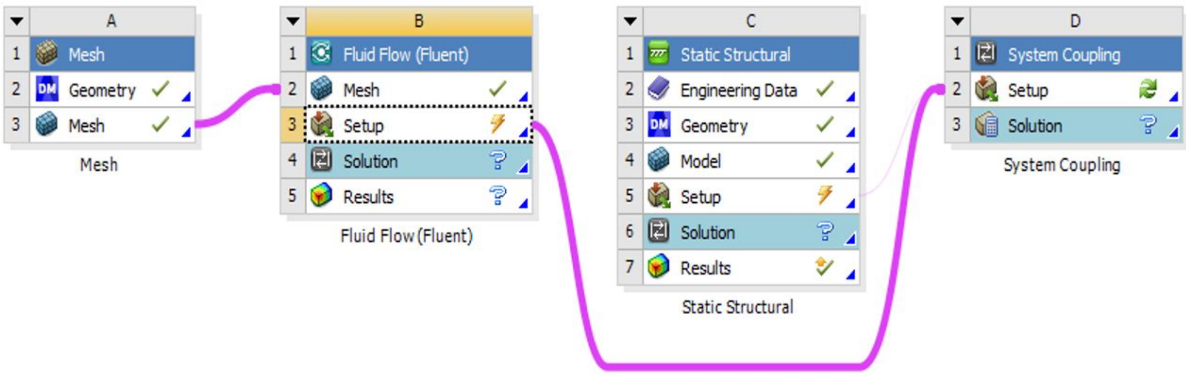


Figure 9 Coupling system for two-way FSI analysis

III. RESULTS AND DISCUSSION

3.1 Mesh Dependency Study

A mesh dependency study for the HAR wing model is done primarily to identify the appropriate mesh for the simulation. As shown in Table 3, three types of meshing have been performed by altering the number of elements, labeled as coarse, base and fine mesh.

Table 3 Results of the mesh dependency study

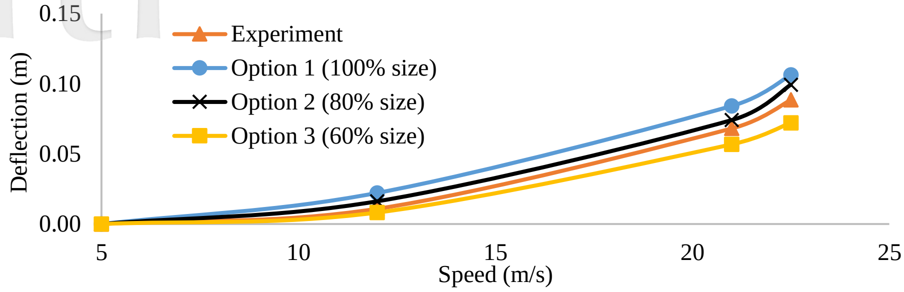
Mesh	Elements	y$^+$	C_L	C_D
Coarse	0.63 x 10^6	0.078	0.00022	0.02110
Base	2.57 x 10^6	0.066	0.00007	0.02113
Fine	5.06 x 10^6	0.061	0.00005	0.02110

This mesh study is performed at an effective angle of attack of 0° with a speed of 15 m/s and using the k-omega SST turbulence model. The results show that the lift coefficient, C_L of the three meshes are approximately zero. In terms of drag coefficient, C_D, the results for the base and fine meshes are almost similar values with a percentage difference of 0.13%. However, the difference between the decimal number for the base and fine meshing for the lift coefficient is 0.0002 and the base mesh is consuming less time with 30 minutes compared to the fine mesh. Therefore, it can be concluded that the base mesh is the best mesh for analyzing the aerodynamic performance of the HAR wing model as it requires less element and less time consumption compared to the fine mesh.

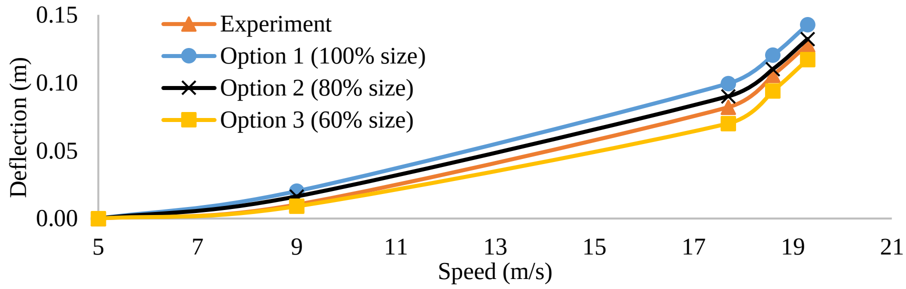
3.2 HAR Wing Deformation with Different Domain Size

Three different domain sizes are analyzed to choose the optimum size to be applied for this current study. The purpose of reducing the domain size is to see the effect that it has on the quality of simulation results for the aerodynamic performance of the HAR wing. The simulation result has been compared with the experimental data of wind tunnel testing on a similar HAR wing design in [18].

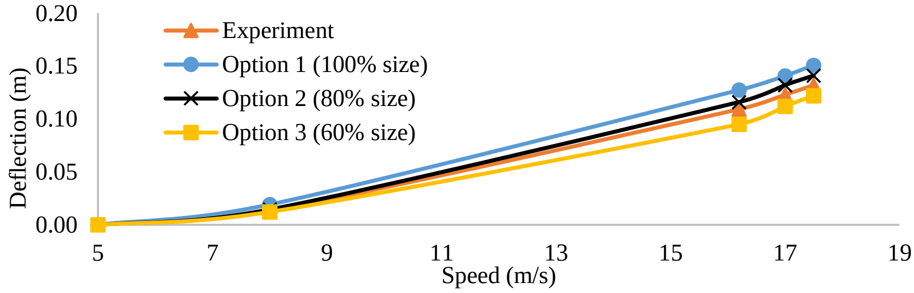
Figure 10 shows the comparison of obtained results for different domain sizes at a few effective angles of attack and speeds. It can be observed that the simulation results are essentially consistent with the experimental results. In addition, simulation results for the second option appear to have very good agreement with the experimental results. The highest percentage difference between experimental and FSI simulation for the second option is seen at an effective angle of attack of 1° and at a maximum speed of 22.5 m/s, which is about 12.28%. On the contrary, the result for option 3 has the highest difference with the experimental result at the effective angle of attack of 1° and at a maximum speed of 22.5 m/s, which is with 18.36% difference. Meanwhile, option 1 has the biggest difference of about 40% between its result and the experimental result, which occurs at an effective angle of attack of 1° and a maximum speed of 22.5 m/s. Based on these findings, option 2 is chosen for this study as the results are very close to the experimental results.



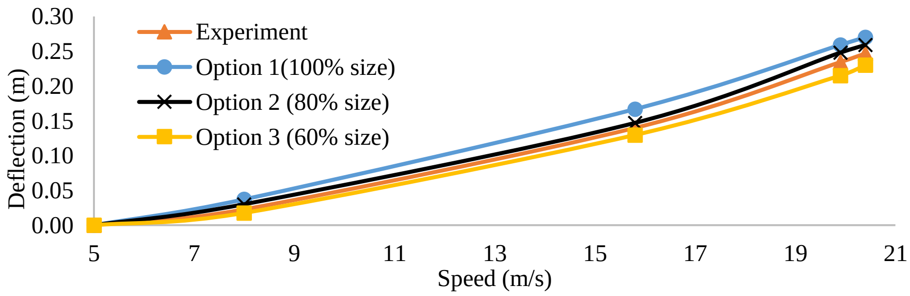
(a) Effective angle of attack = 1°



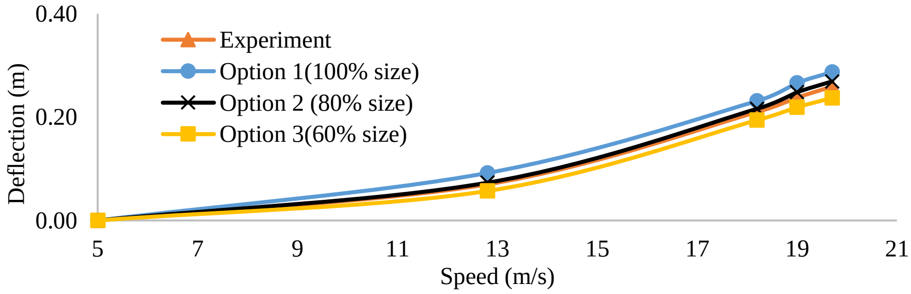
(b) Effective angle of attack = 2°



(c) Effective angle of attack = 3°

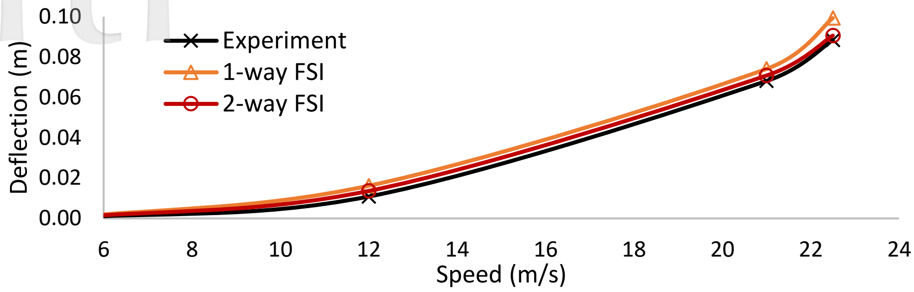


(d) Effective angle of attack = 4°

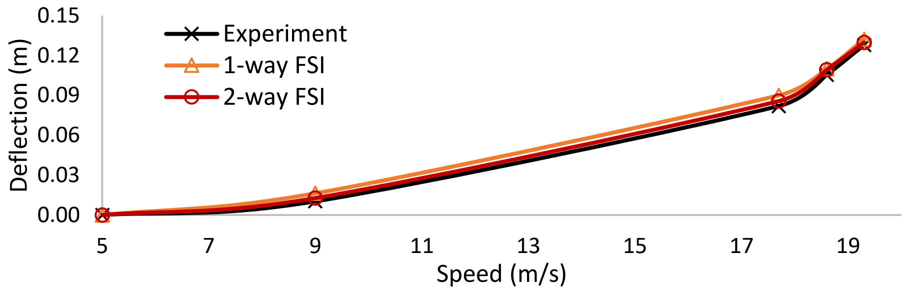


(e) Effective angle of attack = 5°

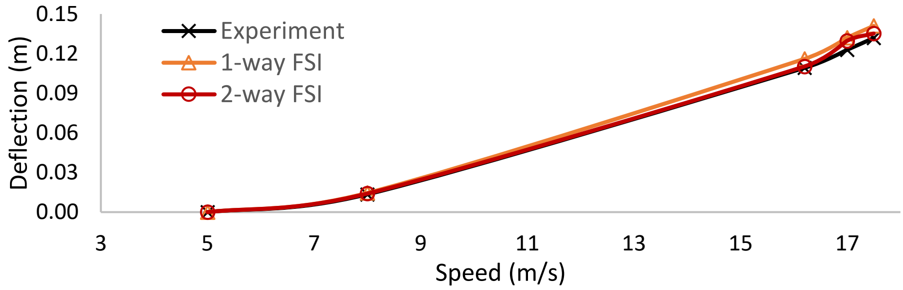
Figure 10 Comparison of results for different domain sizes



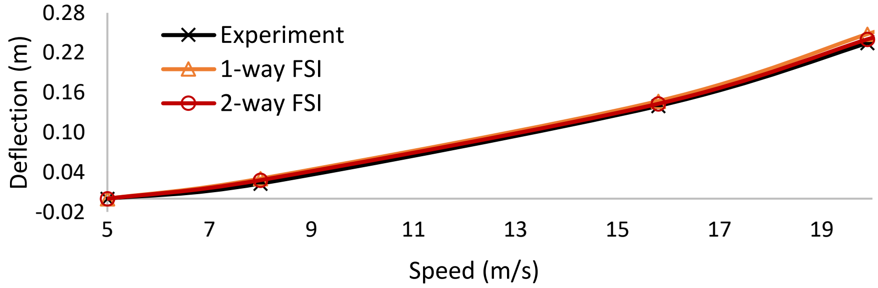
(a) Effective angle of attack = 1°



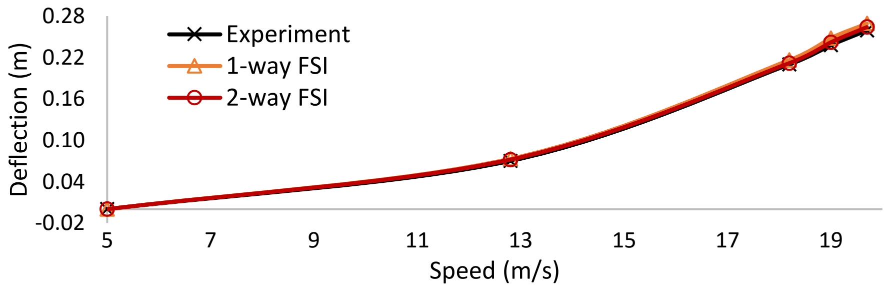
(b) Effective angle of attack = 2°



(c) Effective angle of attack = 3°



(d) Effective angle of attack = 4°



(e) Effective angle of attack = 5°

Figure 11 Comparison of wing deflection results

3.3 Comparison of FSI Analysis Methods

Figure 11 depicts the comparison of simulated HAR wing deflections as obtained from one-way and two-way FSI analysis at different effective angles of attack and speeds. In terms of wing deflection, both FSI analyses have a similar trend to the experimental results. The plot shows that the results of two-way FSI analysis are slightly closer to the experimental results compared to those of one-way FSI analysis. The highest percentage error can be seen at the effective angle of attack of 1° and at a maximum air speed of 22.5 m/s, which is just 3.61%. This can be attributed to the fact that the two-way FSI analysis also considers the effect of the HAR wing's deformation on the fluid flow, which provides the extra data that influences the effect towards the fluid flow, in comparison to one-way FSI analysis. However, it should also be noted that the two-way FSI analysis is time-consuming. In this study, it has been shown that the time duration for the two-way FSI analysis is about two to three times longer than that for the one-way FSI analysis. For information, simulation analysis in this study is performed utilizing the High-Performance Computer (HPC) with 45 processors.

Table 5 summarizes the comparison of the FSI analysis results with the experimental results in terms of percentage error and time consumption. According to the findings, it has demonstrated that the one-way FSI analysis is also capable of being used to appropriately study the HAR wing deformation as the difference between this approach to the experimental results is not that far off.

Table 5 Comparison between the FSI analyses

Comparison Parameter	Angle of Attack (°)	One-way FSI	Two-way FSI
Percentage difference with experimental data (%)	1	12.28	3.61
	2	3.33	1.46
	3	6.93	2.53
	4	4.91	1.54
	5	3.82	1.85
Time Consumption (minutes)	1	20	40
	2	20	72
	3	25	120
	4	30	240
	5	30	300

IV. CONCLUSIONS

Overall, this research study has thoroughly examined the effectiveness of several FSI approaches in determining the HAR wing's deformation. Using the HAR wing model with an aspect ratio of 16, one-way FSI analysis is conducted across various domain sizes, validating the results against the published experimental data in [19]. The mesh dependency study has identified the base mesh as optimal for aerodynamic performance analysis, showing a minimal percentage difference to the experimental data and reduced computational time in comparison to the fine mesh. On the other hand, concerning domain size selection, the second option has proven to be the most effective in producing accurate wing deformation results. Meanwhile, comparing the different FSI analysis approaches, the findings in this study have revealed that two-way FSI analysis has closely approximated the experimental results, though with higher computational demands. Moreover, one-way FSI analysis has also been proven sufficient for straightforward HAR wing deformation analyses while for complex structures, the application of two-way FSI analysis is recommended. This distinction emphasizes the critical need to tailor the analysis method to the specific complexity of the aircraft structure, ensuring precise and effective results in aerospace engineering applications.

ACKNOWLEDGMENTS

The researchers gratefully acknowledge the financial support from the Ministry of Higher Education Malaysia for this research work under their Fundamental Research Grant Scheme: FRGS/1/2020/TK0/UPNM/02/9

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