9th ANKARA INTERNATIONAL AEROSPACE CONFERENCE AIAC-2017-184
20-22 September 2017 - METU, Ankara TURKEY

APPLICATION OF GENERIC AIR VEHICLE SIMULATION MODEL FOR REAL-TIME AERO-ACOUSTIC NOISE COMPUTATION OF PROPELLER AIRCRAFTS

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ABSTRACT

The study conducted in this paper combines previously developed flight dynamics design, analysis and simulation software Generic Air Vehicle Model (GAVM) [Şenipek, 2017] *with helicopter noise computation scheme* [Yücekayalı & Ortakaya, 2015] *for providing a real-time noise computation environment for propeller driven aircrafts. GAVM proposes a generic development environment for different air vehicle configurations. In this paper, the software is utilized for propeller driven aircrafts and the acoustic sphere methodology is integrated to compute the real-time noise levels of XV-15 tilting prop-rotor aircraft in airplane mode for single or multiple observers in ground. Noise levels generated by a propeller for different airspeeds and pitch settings are previously calculated by an aeroacoustic solver for spherical observer grid. These acoustic spheres are used to determine the noise levels for a distant point for a given flight condition when desired. Integration of real time aircraft simulation model enables to compute the real-time aero-acoustic noise generated by the aircraft. In this work, XV-15 aircraft is modeled in GAVM and acoustic spheres are generated by open-source XRotor software. Available acoustic test data belonging to XV-15 tests are compared with the obtained results. Validation of non-linear mathematical model is followed by integrated aeroacoustic real time simulation model in MATLAB Simulink environment. Obtained results for different observers are provided and future usage of the methodology is outlined.*

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INTRODUCTION

In last few decades, advancements in technology lead to an increased number of airplane and helicopter operators. Air vehicles become widespread in several areas ranging from civil transportation to armed military vehicles. Increased usage of aircrafts brings several environmental challenges which force the authorities to strict the regulations on air pollution and noise impact. Several projects and initiatives are supported to reduce the impact on the environment during operations conducted by airplanes, helicopters, tilt-rotors and similar types of air vehicles. Every year, number of complaints related to aircraft noise is increasing at the areas close to airports, military bases and helidecks. Although there are regulations in all phases of manufacturing of an air vehicle, flight path of the manufactured air vehicle should be optimized by considering the noise levels generated on the residential areas. Therefore, a multi-disciplinary methodology is required to predict the generated noise by the aircrafts on the ground.

In this work, a multi-disciplinary approach is presented which combines the flight dynamics, aerodynamics, object oriented programming (OOP), and aeroacoustics to develop a real-time simulation model to calculate the impact noise on the ground. Previously developed GAVM and acoustic hemisphere methodology for helicopters are combined for propeller aircrafts. Since both approaches are compatible for different types of air vehicles, the methodology proposed in this work could be generalizable and be used for different air vehicles. GAVM is developed by using OOP principles to design, analyze and simulate either conventional air vehicle configurations such as helicopters and airplanes or tilting-rotors, prop-rotors, compound helicopters and multi-rotors. GAVM contributes to the air vehicle model side of the work. In other side, acoustic sphere methodology is employed and connected to the flight dynamics simulation model. Observer noise calculation methodology requires airspeed, pilot control settings, rotor orientation and observer(s) position from the flight dynamics model. Computation of noise impact at the observer location is relatively faster than the execution of flight dynamics model which makes the real-time simulation possible. Therefore, the simulation cycle starting from pilot inputs is completed by calculation of real time noise impact at a given observer location.

In this paper, XV-15 tilting rotor aircraft is utilized for GAVM simulation model. For the acoustic sphere generation, an open source software XRotor is utilized. GAVM and XRotor are compared with available test data. Acoustic spheres are generated for different blade pitch angles and airspeed values. Integrated simulation model is used to calculate noise levels for different observers and results are presented. Since the scope of this work is to present the integrated method and to show the possible applications, further detailed researches are left for future works.

GAVM ARCHITECTURE

Generic air vehicle model is a software for design, analysis and simulation of different air vehicle configurations and is coded C++ by making use of object-oriented programming principles. GAVM is designed to solve the engineering problems in aerodynamics, performance and control during the early stages of air vehicle design. GAVM includes several sub-components which exist in an air vehicle such as propeller, rotor, wing, and fuselage. Propeller model is developed based on the propeller analysis code QPROP [Drela, 2006]. QPROP implements the extended version of the classical blade-element/vortex formulation. In GAVM propeller model, QPROP is modified such that the viscous airfoil data is included in the blade element-vortex formulation and modified propeller model is validated [Şenipek, 2017]. Rotor model is based on blade element formulation which incorporates finite state dynamic wake model and rotor dynamics with rigid blade assumption. Second order coupled flapping and lagging dynamics [Chen, 1987] are integrated with Pitt-Peters dynamic inflow [Pitt & Peters, 1981], and Peters He finite state dynamic inflow [Peters & He, 1991] models. Rotor wake interference with wings and fuselage are modeled to take into account of the change in the effective angle of attack and dynamic pressure on the aerodynamic surfaces. There are two approaches for modeling of a Wing object. Wing could be modeled by using table-lookup for 6-DOF aerodynamic coefficients and control surfaces can be defined as either deflected airfoil table or control derivatives. Second method is based on modified Weissinger's second order lifting line theory using viscous airfoil data [Wickenheiser, Adam, & Garcia, 2007] [Wickenheiser, Adam, & Garcia, 2011] and is useful for swept wings. Model for aerodynamic bodies includes table-lookup algorithm for aerodynamic force and moment calculations and can be used as a fuselage and any type of external aerodynamic component.

The sub-components of an air vehicle are attached to a mainframe where 6-DoF dynamics is solved and flight dynamic state derivatives are calculated. Mainframe class holds the information about total forces and moments on center of gravity and includes the routines for 6-DoF rigid body flight dynamics. There is a trim algorithm in GAVM which uses the classical unconstrained optimization of Newton's which searches for an equilibrium point for a defined flight condition by using the whole integrated dynamics and pilot controls. Therefore, any physically possible trim configuration can be analyzed by using the trimmer in the GAVM code. Moreover, total state space representation of an air vehicle around a point of equilibrium is obtained for simulation and control purposes. GAVM is compiled as a shared library and a console project to be used in different areas.

As a result, GAVM proposes a feasible design, analysis and simulation environment for both conventional and advanced configurations in terms of aerodynamics and flight dynamics. Since the model is coded in an object oriented manner, all types of components could be populated and different types of air vehicles as given in Figure 1 can be analyzed if they are defined as a determinate system in terms of flight dynamics and controllability.

Figure 1 Different Types of Rotorcraft Configurations [Johnson, 2013]

GAVM shared library version is also available for simulation and batch analyses which utilizes several export functions for users to manipulate the flight dynamics model. Therefore, it is useful for simulation and control design purposes. Shared library version of the code GAVM can be used any proper tool for further analysis. Therefore, MATLAB Simulink is chosen to simulate the flight and observe the outputs.

AIRCRAFT PROPELLER NOISE COMPUTATION METHODOLOGY

The aircraft noise estimation methodology is a typically utilized database approach which uses pre-compiled physical and acoustical solution to determine noise levels at desired observer locations. The most significant advantage of this methodology is the reduced time cost which enables integration with real time flight dynamics simulations. The solved and stored acoustical field on a spherical boundary surrounding the aircraft is re-used to calculate noise levels at a receiver location while considering the atmospheric attenuation and propagation losses from the surface of the database boundary up to the observer location. Sample representation of acoustic hemisphere method is visualized in Figure 2.

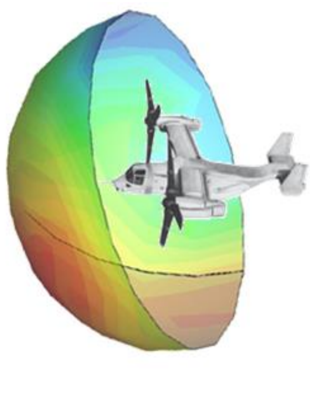


Figure 2 Representation of aero-acoustic semi-sphere

The noise estimation methodology is basically an extension of the study performed for rotary wing aircrafts [Yücekayalı & Ortakaya, 2015] for which similar models are present in the literature for academic and commercial purposes [Conner & Page, 2002]. In this study, the acoustic data for a boundary surrounding the aircraft is determined from XRotor [Drela, XROTOR Download Page, 2011]. XRotor is an open-source code for the design and analysis of propellers and windmills. Validation work related to rotor performance of XRotor is conducted in the previous work [Şenipek, 2017]. Moreover, XRotor features aeroacoustic pressure signature for a given observer point and calculates dB ground noise footprint.

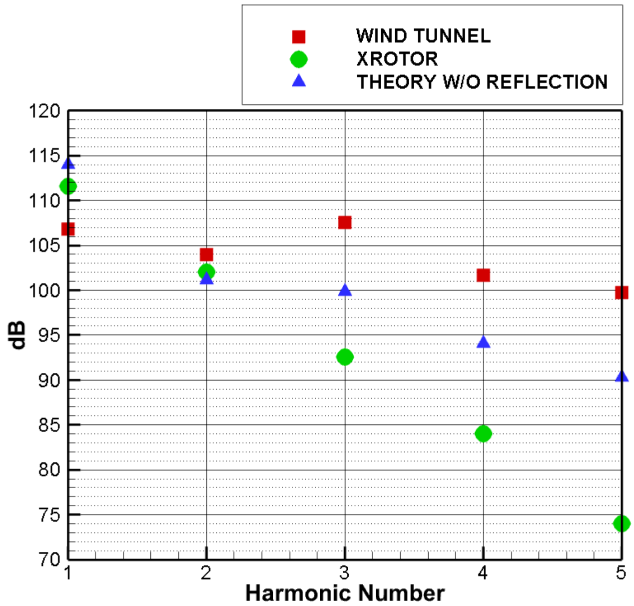


Figure 3 Comparison of XV-15 wind tunnel measurements and XRotor solution. [Lee & Mosher, 1979]

In Figure 3 XRotor results are compared with the wind tunnel measurements and results obtained from a reference generated theory which removes the wind tunnel reflection effects. Results are consistent for the first two harmonics, however; XRotor model cannot capture the higher harmonics. Since the dominant values of sound levels are the first and second harmonics and higher harmonics does not affect the noise levels critically, the results obtained by XRotor can be used with the generation of acoustic spheres. Therefore, XRotor is used to generate acoustic spheres for different blade pitch and different freestream values for the tilting rotor aircraft XV-15 since RPM is constant. Analysis envelope is obtained by GAVM trim analyses for airplane mode. Selected blade pitch angles and freestream velocities are given as follows;

$$V_\infty = [0\ 20\ 40\ 60\ 80\ 100\ 120] \qquad [m/s]$$
$$\theta_{blade} = [12\ 16\ 20\ 24\ 28\ 32\ 36\ 40] \qquad [deg]$$

In Figure 4 sample spheres are depicted for 100 m/s forward velocity for all blade pitch settings. For lower and higher blade pitch settings propeller noise levels are higher since the propeller blade is operating in stall. These spheres are generated for both rotating propellers and their projection into a single sphere is done for simulation model.

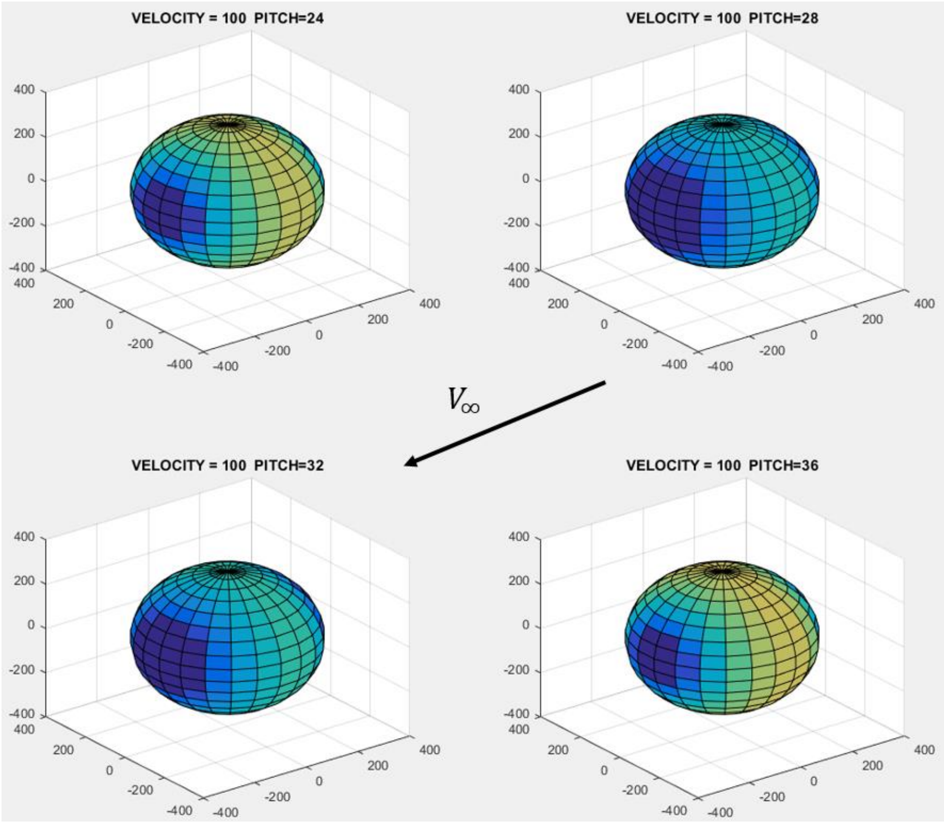


Figure 4 Acoustic spheres obtained for different blade pitch settings at 80 m/s axial velocity by XRotor

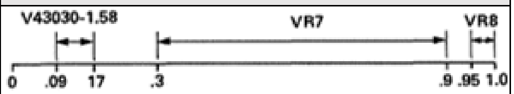
The noise algorithm takes the aircraft position, aircraft attitude and observer locations as inputs, properly transforms the vector from aircraft to observer location and related noise sphere database with heading, pitch and roll angle. Then the noise estimation algorithm takes azimuthal and elevation angles of the receiver with respect to the aircraft representing the direction and the slant distance to the receiver from the aircraft as inputs. Taking ambient temperature, humidity and pressure values into account, the algorithm calculates the noise impact and frequency spectrum at the observer location. The propagation is performed assuming the acoustic ray paths are straight lines and no wind condition. This approach brings the ability to estimate noise levels in real time while enables skipping the computationally expensive calculations by pre-compiling and storing them. The noise footprint typically for a specific flight condition or if the database is supplied, noise footprint for the whole operation can be determined accurately and efficiently. One of the main advantages of utilizing the sphere approach is that the acoustic data can be generated by analysis at desired fidelity level, test or combination of test and analysis. Furthermore, the accuracy of the acoustic estimation depends on the accuracy of the noise database and does not vary the architecture of the tool developed with this study. Therefore, the scope, fidelity or accuracy of the acoustic database can be altered without affecting the concern of this study.

The essence of this study is to improve the basic idea of the typical acoustic footprint generation approaches for aircrafts by assembling the noise estimation methodology with sphere approach with a flight dynamics simulation model. As a result, a better representation for the vehicle flight in time based domain along a prescribed path or control schedule is achieved.

NON-LINEAR AIRCRAFT MODEL

XV-15 tilting-rotor aircraft is convenient for propeller aircraft noise analysis study since the availability of aircraft data. XV-15 is modeled by using Propeller, Fuselage and Wing classes of GAVM [Şenipek, 2017]. XV-15 has two interconnected 3.81-meter radius prop-rotors having three blades [Maisel, Giulianetti, & Dugan, 2000]. Aeroacoustic simulation case is implemented for the XV-15 tilt-rotor aircraft for only airplane mode since the available acoustic analysis capability is limited by axial propellers.

Table 1 Specifications of XV-15 Tilt Rotor Blade

Proprotor	
# of blades	3
RPM (Helicopter)	589 [rev/min]
Geometry	
Radius	3.81 [m]
Mean Chord	0.411 [m]
Solidity	0.103
Airfoil Profiles (VR7 & VR8 tip)	
Twist	-47.0 [deg]
Precone angle	2.5 [deg]

Details of geometric properties of XV-15 are given in Table 2. XV-15 aircraft wing has 9.8-meter span length to provide lift for airplane mode. Flaps and flaperons are used to generate additional lift for transition flight and to reduce the download effects for hover. Fuselage and wing aerodynamics are modeled by the help of experimental wind tunnel test data [Weiberg, 1980]. Wind tunnel tests provide valuable data for different angle of attack, sideslip, nacelle tilt and flap deflections. Experimental data is imported into GAVM fuselage and wing models as lookup tables.

Table 2 XV-15 geometric specifications

Weight		**Horizontal Tail**	
Design	5896 [kg]	Span	3.91 [m]
Empty	4574 [kg]	Area	4.67 [m^2]
Gross	6010 [kg]	Chord	1.19 [m]
Wing		Airfoil	NACA 64A015
Span	9.8 [m]	Aspect Ratio	3.27
Chord	1.6 [m]	**Vertical Tail**	
Area	15.7 [m^2]	Area	4.69 [m^2]
Airfoil	NACA 64A223	Airfoil	NACA 0009
Aspect Ratio	6.12	MAC	1.13 [m]
Sweep	-6.5 [deg]	Aspect Ratio	2.33
Dihedral	2 [deg]	**Proprotor**	
Length	12.827 [m]	No of. rotors	2 (interconnected)
Width	17.424 [m]	RPM (helicopter)	589
Height	3.861 [m]	RPM (airplane)	517

Airplane mode validation study is conducted by using the flight test data for airplane mode [Maisel, Giulianetti, & Dugan, 2000]. Figure 5 illustrates the required power values for level flight airplane mode from 160 knots to 240 knots of airspeed. Limitation of the generated dynamic model is the fidelity of the aerodynamic data provided into GAVM model. Within the limitation of available test data obtained results shows consistency with small over-estimation in required power values.

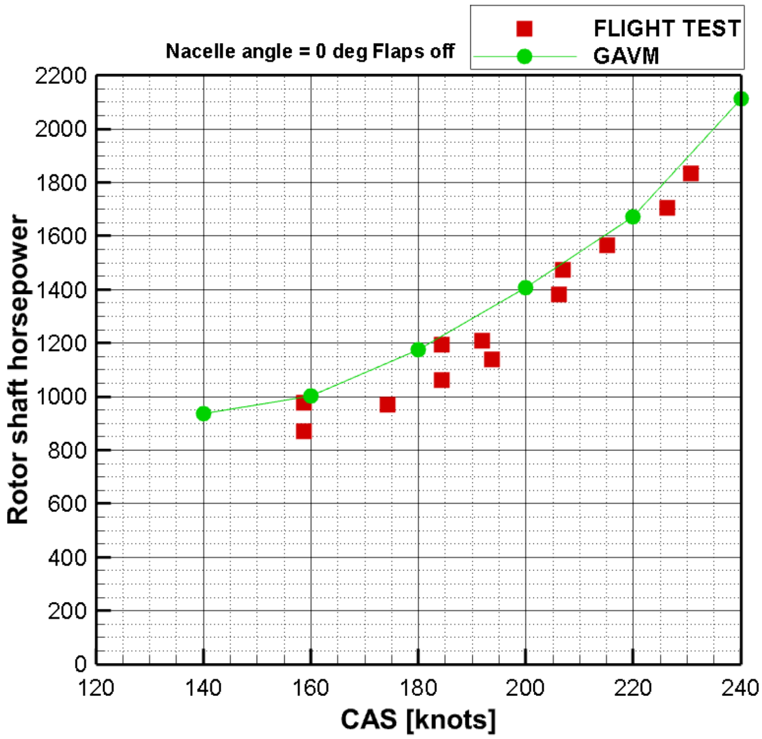


Figure 5 XV-15 comparison of shaft power with airspeed in Airplane mode

INTEGRATED SIMULATION MODEL

Integrated flight simulation model is generated in MATLAB Simulink by combining acoustic sphere methodology with GAVM shared library version with XV-15 airplane mode non-linear model as given Figure 6. Simulation starts from a configured trim condition and steady flight is simulated by providing trim inputs. Acoustic spheres are integrated into simulation model with an interpreted function which calculates the noise of the aircraft with respect to an observer located in a certain position. Acoustic calculation code requires inputs of aircraft speed, blade pitch angle, aircraft orientation, aircraft position and observer position. In each timestep, these parameters are supplied into the acoustic calculation and noise is calculated. When considered the execution time of acoustic calculation, real time frequency of 100 Hz for a standard personal computer, the aim of real time acoustic simulation is achieved.

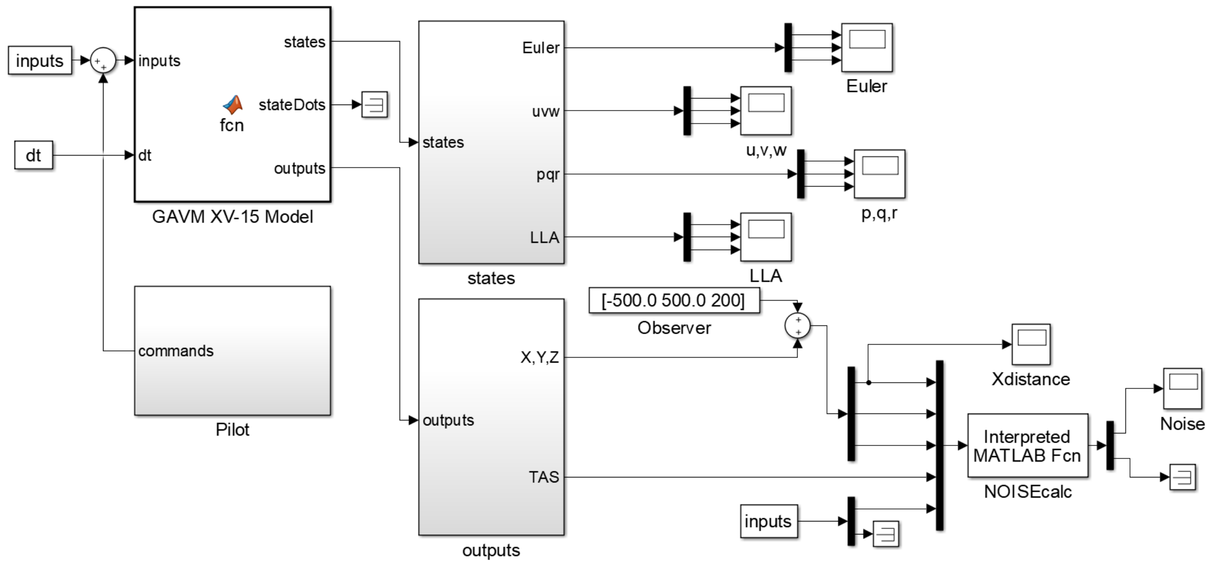


Figure 6 Flight simulation model of XV-15 with noise calculation methodology

By using the simulation described in Figure 6, observers are placed three different locations and 150 knots steady flight is performed. Generated noise levels are plotted in Figure **8** for these three observer locations. The closest observer is Observer 1 which is located just below the flight path of aircraft and the last observer stays 500 feet starboard.

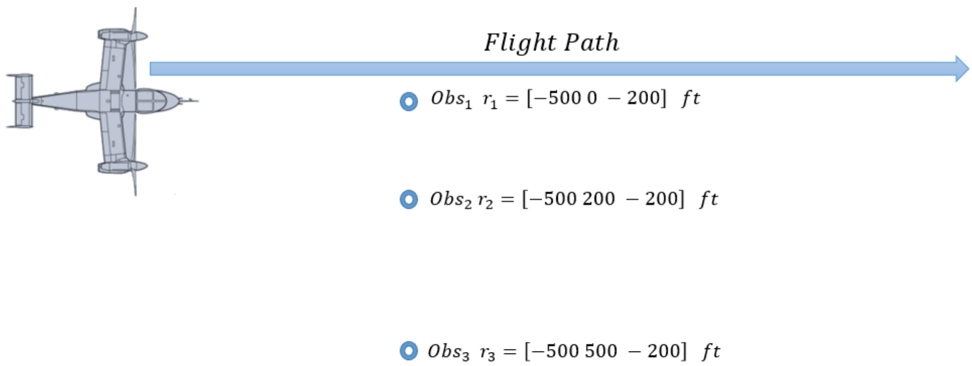


Figure 7 Representative sketch of observer locations and flight path

In Figure 8 flight simulation is performed and noise levels are obtained for three different observer locations. As given in the figure, the highest level of noise is sensed at Observer 1 as expected at the instant when aircraft passes through. However, the noise levels are overlaps and the noisiest observer changes as the aircraft moves away. As the aircraft goes far away Observer 1 hears the lowest level of noise since it is placed at just the backwards of the aircraft with respect to the flight path which can be seen in Figure 4 and Figure 9.

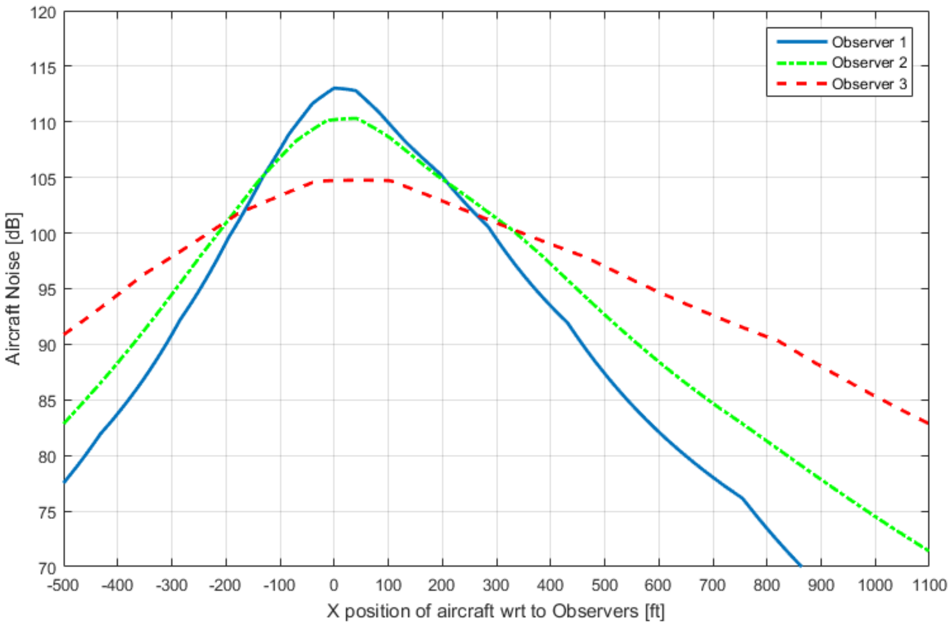


Figure 8 Noise levels at observer locations for150kts flight at 200 feet ISA conditions

In Figure 9 noise dB contours are plotted for XV-15 160 knots forward flight simulation. Noise contours represents the generated ground noise levels below 100 feet of the aircraft for a given instant. The behavior described in the previous figure is clearly shown in this figure.

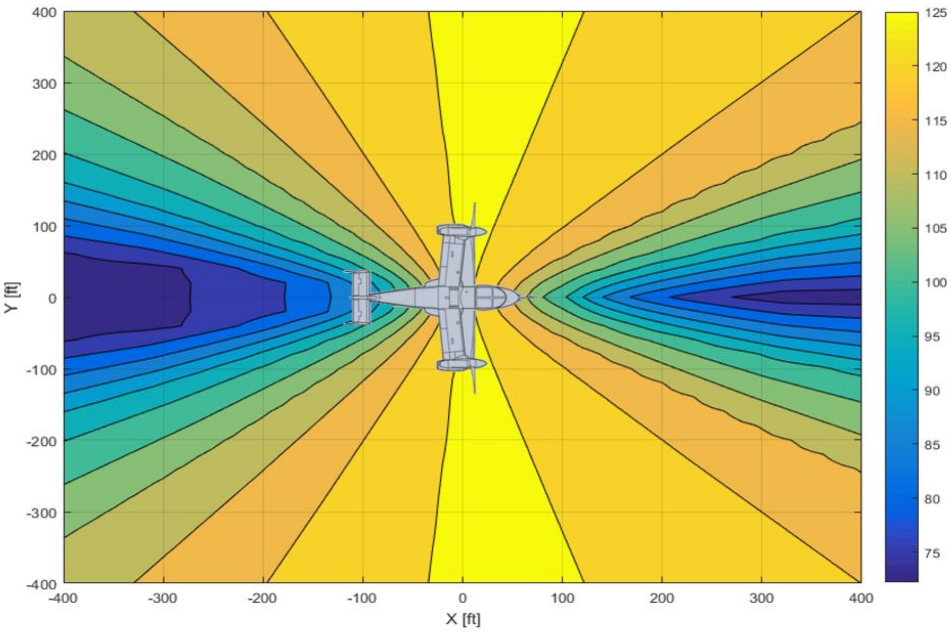


Figure 9 Distribution of ground noise from 160 knots level flight at 100 feet height for 800x800 ft^2 ground area

Calculated noise levels by XRotor include periodic loading and thickness noises. Broadband noise is not included in the theory. Higher fidelity tools such as free wake solvers and CFD solvers or existence of experimental data will provide better resolution in generation of acoustic spheres and calculated noise levels without any change in the developed simulation architecture.

REMARKS

- Generic air vehicle design, analysis, and simulation software is developed and validated under the Master Thesis in METU Aerospace Engineering.
- Object oriented nature of GAVM enables to integrate with other software as a shared library.
- Since GAVM has a generic modeling interface, it is applicable to different air vehicles platforms easily.
- Previously, an aero-acoustic computation scheme was developed for helicopters. As stated in previous chapter propellers could be assumed as a rotor without hinges in climbing flight. In this case, with the available methodology it is possible to calculate the aero-acoustic noise of single and multiple propeller aircraft.
- XRotor open source software is utilized for aero-acoustic solver and used for acoustic sphere generation.
- XV-15 tilt rotor aircraft is modeled by using GAVM shared library version and flight dynamics simulation is developed. Integrated aeroacoustic simulation results are obtained.
- The accuracy and the correctness of the methodology highly depend on the fidelity of aerodynamic and acoustic solvers.
- This simulation methodology may be utilized for further researches such as minimal noise flight path optimization, air traffic optimization, and quieter approach trajectories.

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