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Computational Time Optimization in Airwake Vortex Mapping for Rotorcraft Flight Simulators

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Abstract

In the following paper, we demonstrate the use of Fourier Transform as an integrated method to approach the reduction of computational cost in vortex mapping for rotorcraft flight simulators. Fourier Transform is used to analyze airwake data, both in time and spatially, to understand the structure of readily occurring air vortices on the flight deck of a Simplified Frigate Ship configuration (SFS-2). The result was both a clear and descriptive amplitude spectrum for a particular range of positions on the flight deck. The technique proved to be promising in reducing computation and has the potential to improve rotorcraft flight simulation while maintaining a high degree of fidelity.

I. Introduction

Flight simulators are faced with the unique challenge of trying to replicate complex, natural flight conditions in real time, and simulations are often only accomplished at the cost of extremely large amounts of computation. Even so, as our knowledge of the conditions that affect flight grows so too can our ability to more accurately replicate the situations that pilots will face on a day-to-day basis. Towards the goals of improving safety, as well as further understanding the conditions of flight, this development of simulation fidelity seems fundamental. Of course, this type of improvement means a necessary increase in computing power to calculate the further variables and flight states that the aircraft faces. To account for this computational inflation simulators need to employ concise mathematical models that accurately represent flight environments, both to further understand the conditions and in order to optimize data processing costs.

One of the many complex conditions affecting flight is airwake turbulence, especially the effect of vortices; a problem that arises in many situations but explicitly in the case of aircraft-supporting sea vessels as a result of their superstructures. Rotorcraft, and Helicopters in particular, are prone to flight instability when moving through these vortices due to their large surface areas and rotor mechanics. The inclusion, mapping, and modeling of these vortices thus becomes an integral part to any rotorcraft flight simulator but simultaneously drives greater computational cost.

The goal of this investigation is to mathematically reduce the computational cost, and therefore optimally reduce the time, necessary to accurately model and map vortices on a ship's flight deck. The method used to explore the possibilities to this end were as follows. Using a Navy-provided velocity field we first took a Fourier Transform in time across our x-axis range with respect to a specific y and z-positions. We then plotted this data's Single-Sided Amplitude Spectrum in the frequency domain to identify the frequencies and x-positions at which the greatest amplitude readings were measured.

Using these frequencies and x-positions, we went back to our original velocity field and took a Fourier Transform in space across our y-axis range for our identified frequencies and x positions of greatest amplitude. Lastly, we graphed this transform's Two-Sided Amplitude Spectrum with respect to y position.

Using these four steps we worked to accurately begin mapping the position of vortices in the given velocity field. If this process is successful it could reduce computational cost to simulators that currently employ less innovative approaches.

II. Geometry and the Simplified Frigate Shape (SFS-2)

In order to explore the use of Fourier Transform in vortex mapping a Navy-provided data set was used. This data set was produced through computational fluid dynamic (CFD) simulation of a Simplified Frigate Ship (SFS-2), as seen in Figure 1. The simulation measured velocity in the $x(U)$, $y(V)$, and $z(W)$ directions as well as time. Data was collected at 43,493 different positions: 61 points in x, 31 points in y, and 23 points in z; all values are in steps of 2 feet. The simulation took place over 125 time steps of 0.373 seconds.

The area of interest for developed vortices is the flight deck located behind the ship's superstructure. For this reason, the origin is defined at directly behind the superstructure's rear wall, port side, and at flight deck level. Motion in the positive x direction would be towards the rear of the ship, likewise, positive y would be starboard, and z would be above the flight deck.

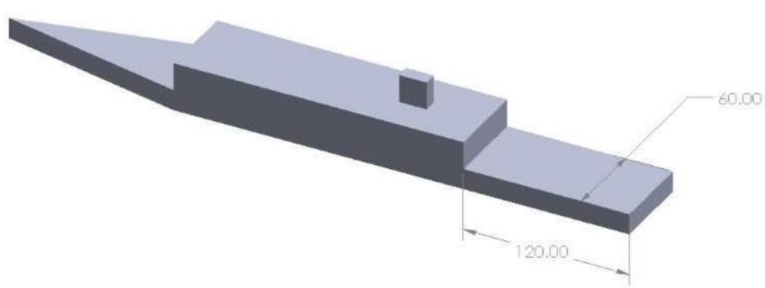

Figure 1: The Simplified Frigate Shape (SFS-2) used to produce the original data set through CFD.

III. Mathematical Theory

This investigation principally made use of one mathematical modeling technique, Fourier Transforms. The Fourier Transform takes the form seen in Equation 1 below.

$$f(\omega) = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt \quad [1]$$

Here ω is the frequency of the function, and $f(t)$ is the time domain function where t is the variable of interest.

Fourier Transforms are used in decomposing a signal in the time domain into the frequencies that help construct it in the frequency domain. This process effectively reduces the number of dependent variables needed to express the function that's producing the original signal in the time domain because it is simply a function of frequency. In order to determine these frequencies Fourier Transforms are often plotted versus frequency as amplitude spectrums. This allows one to identify points of greatest amplitude significance and subsequently the characteristic frequencies at which they occur.

IV. Procedure

Our first step was to select a range of velocities over which to analyze the velocity field. In this investigation we chose to begin at the point $x = 0$, $y = 0$, $z = 0$, as defined by the origin discussed above, and move across the x range of position. This allowed us to observe characteristic frequencies across this range and whether they were the same from position to position. In terms of velocity, we chose to use U, the velocity in the x direction, for convenience of computing but also because the x position and y position are the two most important in vortex mapping.

Our original data set, the velocity field, was an array of velocity values in x, y, z, and t (time). We organized this set 4-dimensionally in MATLAB and then plotted U versus time across our defined range of $x = 0 \rightarrow 61$, $y = 0$, $z = 0$. The ship's average x-velocity of 30 knots was removed from the data set and the relative U was plotted versus time once more, an example of this plot can be seen in Figure 2.

Using each unique velocity function across the x range, we took a Fourier Transform in time and plotted the Single-Sided Amplitude Spectrum versus frequency. This produced a plot at each position for the x range; an example of this plot can be seen in Figure 3. Using these plots, the peaks of greatest significance, the frequencies, and locations within the set at which they occur, were all recorded. Significance was determine using standard deviation; any peak of amplitude greater than two standard deviations from the mean peak height was stored.

Following the identification of frequencies and positions of amplitude significance, we took the first frequency and position. At this frequency and position, we moved across the y range to observe U once more. With this data we plotted U versus y-position, as seen in Figure 4. We then took a Fourier Transform of this data and plotted its Two-Sided Amplitude Spectrum versus y-position to observe how amplitude might change in space. The resulting graph can be seen in Figure 5.

V. Results

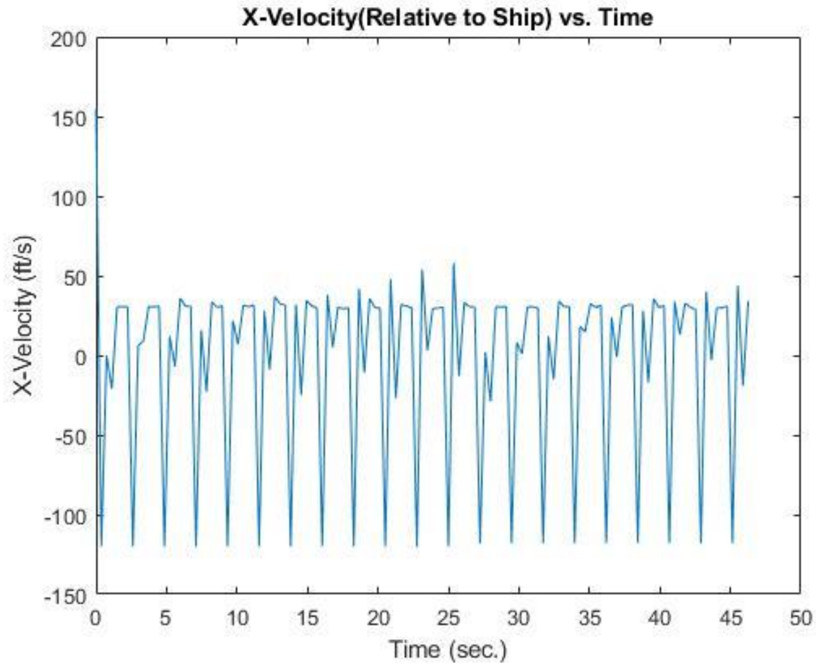

Figure 2: Velocity, U, in the x-direction (relative to the ship) plotted as a function of time for a particular x, y, and z location.

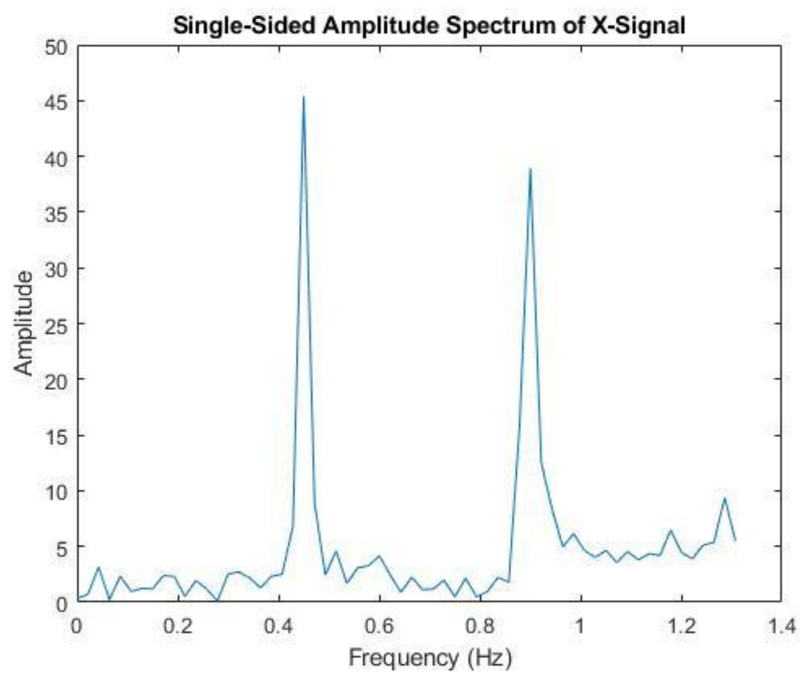

Figure 3: The Single-Sided Amplitude Spectrum of the x-Signal, as a function of frequency, for a particular x, y, and z location. The frequencies are measured to be $\omega_1 = .4503\ Hz$ and $\omega_2 = .9005\ Hz$.

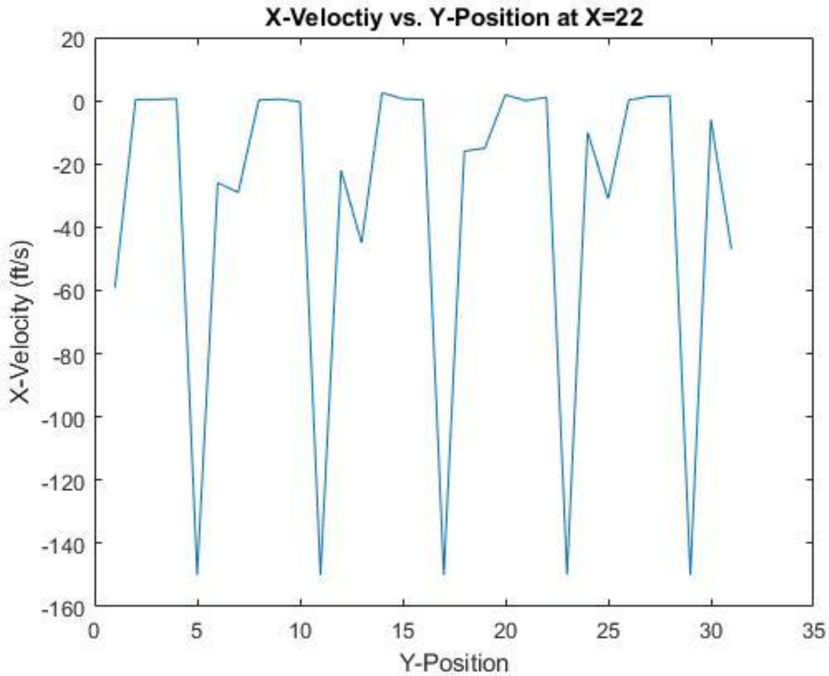

Figure 4: X-velocity, U, as a function of the y-position, at location $x = 22$.

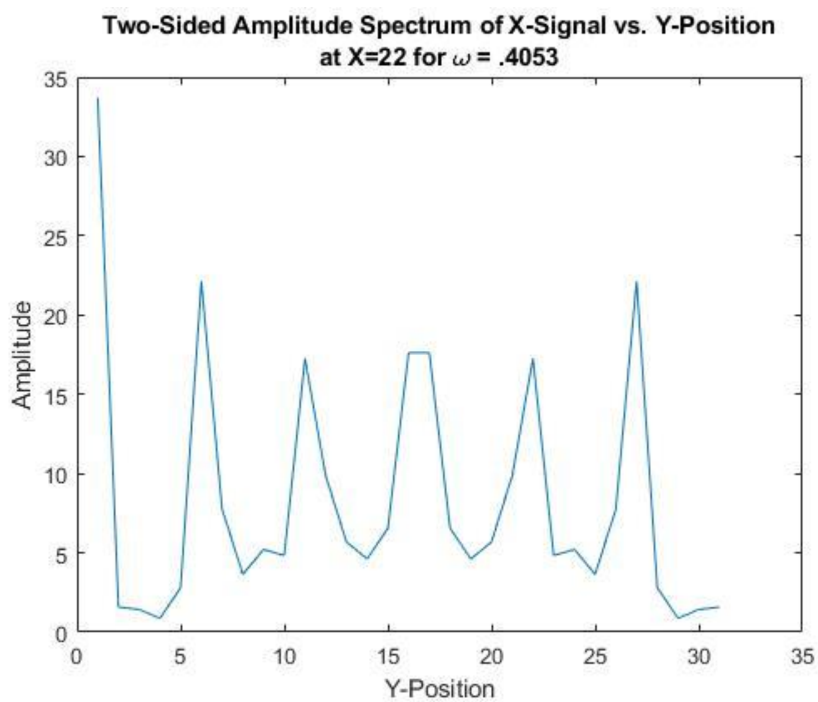

Figure 5: The Two-Sided Amplitude Spectrum of the x-signal as a function of the y-position at the location $x = 22$, and for the frequency $\omega_1 = .4503\ Hz$.

VI. Analysis

If we first look at Figure 2 above it can be seen that the velocity U with respect to time is relatively periodic. However, the variability of the plot, and its failure to precisely fit any type of harmonic suggested the possibility of multiple characteristic frequencies governing the function. This makes the use of Fourier Transform as a mathematical tool for analysis a strong one. In Figure 3 the Fourier Transform of the prior velocity data is seen with two very distinct peaks, both are significant by our earlier definition (lying two standard deviations outside of the mean). An amplitude of nearly zero at a frequency of zero also shows that the ship's velocity, a constant in this situation, has successfully been removed from the function. The frequency and location of each of these peaks was gathered. Across the range of x-values for which this process was carried out, each frequency for the first peak was $\omega_1 = .4503\ Hz$ and each location was $x = 22$; each frequency for the second peak was $\omega_2 = .9005\ Hz$ and each location was $x = 43$. This would suggest that these two frequencies are the characteristic frequencies of the x-signal and should be used to further evaluate the velocity field's behavior in space.

Looking at Figure 4 we can see U, the x-velocity, as a function of the y-position for a particular x, $x = 22$. The velocity is again periodic though not harmonic, making Fourier Transform a strong tool for analysis once more. In Figure 5 we can see the Two-Sided Amplitude Spectrum of this velocity for the first frequency identified in Figure 3, $\omega_1 = .4503\ Hz$. The first peak is erroneous considering that we removed no potential constant (e.g. a cross wind) from the velocity data before Fourier Transform. The other five significant peaks are of importance, as they show the y-position of what appear to be trailing vortices. Furthermore, the peaks are all measured to be 10 feet apart (5 y-position units of 2 feet each), this is significant because it represents a level of symmetry across the wake and between the trailing vortices.

Critical to consider through this process is the relative error that it introduces itself at each step, particularly in the selection of significant peaks. Given that many more than just two peaks are produced in the Fourier Transform plotted in Figure 3 means that there are more than just two frequencies contributing to the function in the frequency domain. These frequencies are not considered, and despite the fact that this investigation only examined one frequency at a particular position, they would likely not be considered moving forward and thus introducing a level of inaccuracy to the model. Furthermore, the same could be said for the analysis of Figure 5. There are smaller peaks considered to be insignificant that could still be trailing vortices themselves, to not include them introduces some error we must consider in constructing our model.

VII. Conclusion

The mathematical technique of Fourier Transform proved to be a powerful tool in identifying contributing frequencies that make up velocity signals of airwake. In this investigation we were able to use Fourier Transform to identify two characteristic frequencies of the x-signal across the x range at particular y and z locations. Using the first of these two characteristic frequencies we were able to use a second Fourier Transform to evaluate the x-signal across the y range at particular x and z locations. This analysis showed us that there are likely five significant trailing vortices evenly spaced by 10 feet across the y range.

While the process of this evaluation introduced some level of error in its analysis, it is relatively small and in the scheme of producing a simulator of optimally high fidelity and lower computational cost, the error is likely inconsequential. Taking all these factors into consideration, the use of Fourier Transform, especially in the process described in this paper, as a method of spatially mapping vortices for the airwake of a Simplified Frigate Ship (SFS-2) appears to be promising.

Though this investigation may serve as a starting point, more work remains to be done in order to develop, refine, verify and explore this process further. We only observed the x-velocity and for a very limited number of positions. Calculation and development across all three axes in time would help synthesize the process (though a holistic analysis of x and y with subsequent transforms in space may also work) and produce a comprehensive mapping of the vortices present in this velocity field. Furthermore, this investigation only analyzed one of the two frequencies that it discovered in transforming its initial x-velocity data. An analysis of the second could confirm the findings of this paper to an extent, as well as contribute to analysis of spatial decay in vortex intensity.