The Effect of the Number of Modes and Feed Locations in Angle-of-Arrival Estimation Using a Multimode Antenna

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Abstract—Given a multimode antenna and a discrete number of modes, the number of modes used and the farfield patterns of the modes impact the angle-of-arrival (AOA) estimation error. This paper presents an analysis of AOA estimation for a multimode structural radiator for a varying number of modes, where each mode is excited through a different feed location on notional two-dimensional crossed plates. Empirical results for AOA estimation errors versus the number of modes and the location of the feeds for each mode are presented using the maximum likelihood method estimator.

I. INTRODUCTION

Airborne angle-of-arrival (AOA) estimation becomes challenging when the frequencies of interest are low enough that the aircraft structure is on the order of, or smaller than a wavelength. In this scenario beamforming using a linear array of half-wavelength antenna elements is impossible. The problem becomes creating a receive array using the aircraft as the radiating structure and then using that array to estimate the AOA of a signal of interest.

In the early 1950s, Granger [1], [2] demonstrated in the lab that the structure of an aircraft could be used to predictably radiate signals with wavelengths on the order of twice the wingspan. Since that time, structural antennas have been proposed for communication purposes and demonstrated on aircraft [3] and naval vessels [4], [5]. The difficulty then and now is that the low input impedance of the feeds results in poor radiation characteristics. The low input impedance is due to the long wavelength, with respect to size of the nonideal radiating structure.

The Theory of Characteristic Modes was first introduced by Garbacz and Turpin [6] in 1971. Later that year, Harrington and Mautz [7] refined the theory and applied it to bodies of revolution and wire objects [8]. Since that time, the Theory of Characteristic modes has been applied to aircraft and ships. Cabedo, et. al., [9] revisited characteristic modes and applied

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them to plates and folded radiating ground planes for cell phone handsets.

Akers [10] and Dixon [11] addressed direction finding using aircraft with structurally integrated antennas with maximum structural extents about the size of a wavelength. The AOA estimation results shown were favorable, but the dependence of AOA estimation error on the number of feeds and the feed locations used to excite the aircraft structure were not investigated.

This paper investigates the effects of the number of modes used in the AOA estimation and the locations of the feeds used to excite those modes on the structure. Throughout this paper, each mode is excited by one feed point having one receiver channel. This analysis is performed using two-dimensional crossed plates whose length in each dimension is on the order of a wavelength. The azimuth AOA is estimated using a super-resolution technique, namely the maximum likelihood method (MLM). Corresponding to sampling theory, the number and spatial diversity of the feed point locations determines the resolution and ambiguity of the AOA estimation. Because the wavelengths of the signals considered are too long to afford much spatial separation between the feeds, there should be a number of modes above which little benefit is gained compared to the computational costs of including them in the estimation.

The paper will present the simulation parameters, the corresponding results, and then conclusions.

II. SIMULATION PARAMETERS

The *platform* for this analysis is a two-dimensional flat plate plane shown in Fig 1. This plane was used as the radiating structure in this analysis. Two frequencies, 4 MHz and 11 MHz, were considered such that the larger dimension of the plane was less than one wavelength (actually 0.54 of a wavelength) for 4 MHz and greater than one wavelength (actually 1.49 wavelengths) for 11 MHz. This choice of frequencies allowed for analysis of the effect of relative platform size with respect to signal wavelength on the accuracy of AOA estimation.

The resulting current distribution for the first characteristic mode for a uniform azimuth pattern at 4 MHz is shown in

Figure 1. Dimensions of the 2D shape used in AOA estimation [12]

Fig 2. Following the Theory of Characteristic Modes, each mode has a unique current density over the surface of the radiating structure. To excite a single mode, the radiating structure would ideally be fed with an infinite number of feeds to match the current density over the entire structure. However, to minimize the number of feed points, and thus the system complexity, each mode was approximated by exciting the two-dimensional plane in Fig 1 with a 10-inch monopole feed placed in the location with the highest current density. For the simulation, a total of 16 independent, characteristic modes, corresponding feed points, and resulting farfield transmit patterns were generated for both 4 MHz and 11 MHz in [12]. Using the reciprocity, the transmit feed voltages required to approximate the farfield pattern of each mode were converted to received voltage at the feed for AOA calculations.

To explore the effect of the number of modes on AOA estimation, the maximum likelihood method (MLM) described by Penno and Pasala [13] was used. The MLM compares the array response to an incident wave of arbitrary AOA to an array of steering vectors, known as the array manifold. The array manifold may be viewed as a look-up table containing the array response or steering vector for each possible elevation and azimuth combination, (θ, ϕ) , respectively, of an incident plane wave with a given frequency. The steering vector is the array response to a farfield plane wave with known characteristics, absent noise and interference, emitted from a given AOA. The steering vector is comprised of the individual responses of each receive element (mode) comprising the array. The array manifold used in this analysis was comprised of steering vectors for every one-degree increment in azimuth for a single elevation coplanar with the two-dimensional plane, an elevation angle also referred to as waterline.

For this investigation, only azimuth AOA estimation for horizontally, or ϕ -polarized incident plane waves were considered. For lowband airborne applications, aircraft have little vertical extent, and therefore poor response to vertically polarized

Figure 2. Current distribution on 2D shape excited by 4 MHz incident field [12]

Figure 3. 4 MHz farfield patterns for 16 modes. Scale ranges from -60 dB (inner circle) to -25 dB (outer circle). Feed points for 10, 14, 15, 16 have the highest input impedance.

incident fields. The incident plane wave was simulated to be incident on the platform at waterline, and the additive, complex noise was assumed to be white with Gaussian distribution. These assumptions were used as a best-case scenario. Simulations were performed using arrays consisting of 16, 8, and 4 modes with incident signals of 4 and 11 MHz. The number of modes required for accurate AOA estimation directly impacts the complexity of system design and the computational burden. For the simulations using eight and four modes, the modes with the highest input impedance, and therefore, the largest average directive gain, were chosen. It is important to note that the feed points are not collocated for both frequencies; the feed points for the 4 MHz array are different than those of the 11 MHz array. The 4 MHz far field patterns are shown in Fig 3. Similarly, the 11 MHz patterns are shown in Fig 4.

The signal-to-noise ratio (SNR) at the input of the receiver was set at -5 dB by adding complex white Gaussian noise to the received signal. Because the radiating structure is an

Figure 4. 11 MHz farfield patterns for 16 modes. Scale ranges from -60 dB (inner circle) to -25 dB (outer circle). Feed points for 11, 12, 13, 16 have the highest input impedance.

inefficient antenna for each mode, as evidenced by the farfield patterns in Figures 3 and 4, the resulting input SNR required to achieve the presented results for each sample in the data vector was much higher than -5 dB. The amount of noise power added to the incident signal to achieve this SNR was calculated using the average power in the received signal at each incident azimuth AOA. The azimuth AOA of the simulated incident field was varied between 0° and 345° in 15° increments, and 200 Monte Carlo simulations were run for each incident AOA. The signal was sampled 1024 times to reduce the effects of sampling. Each simulated measurement vector had a separate noise vector added to it. The 1024 samples translates to an integration time of 25.6 microseconds at 4 MHz and 9.31 microseconds at 11 MHz. The sampling frequency was set at 10 times the signal frequency. Averaging the SNR across 200 observations, 1024 samples, and all incident azimuth angles for each of the four feeds with the highest input impedances resulted in an unrealistic SNR of approximately 80 dB.

Other factors considered when reducing the array included spatial location of the feeds and the far field pattern of the excited modes. The spatial distribution of antenna elements in an array is crucial in a beamforming AOA system. However, the spatial diversity of the feeds on a multimode antenna may not have the same impact on an amplitude comparison system, such as MLM. For this reason, 25 random combinations using 4 of the 16 modes were used to create 25 different arrays. In an attempt to investigate the effect of the feed locations, the same complex Gaussian noise was added to each of the 25 combinations. The noise added to each combination was the noise resulting from the four highest impedance modes. Again, for each of the 25 four-mode combinations, the azimuth AOA of the incident field was varied between 0° and 345° in 15° increments, and 200 Monte Carlo simulations were run for each incident AOA.

Figure 5. Comparison of the azimuth estimation error generated by 16, 8, and 4 modes for a 4 MHz incident field

III. SIMULATION RESULTS

The performance of the simulated system was analyzed using the error in the estimated azimuth AOA as well as the standard deviation of the error. The error in the azimuth estimate is simply defined as the difference between the estimate and the true azimuth. These measures facilitate comparison of the performance based on the number of modes used to generate the results.

The azimuth estimation error for a 4 MHz incident field is shown in Fig 5. Some data points for the eight and four mode simulations exceed the range of the plots. The estimation error for all three mode configurations have a similar trend, though the magnitudes of the errors increase as the number of modes was reduced. As discussed in the previous section, the average SNR at the input of the receiver per measurement sample for each scenario was -5 dB.

A comparison of the system performance for the 4 MHz incident field using the standard deviation of the error is shown in Fig 6. The system performance for 16 and 8 modes was similar, though eight modes had a comparatively high standard deviation at 0° . Using four modes for AOA estimation for a 4 MHz incident field resulted in large estimation errors at 0° and 180° . This inability to accurately resolve signals incident on the platform at these angles was attributed to the dipole-like farfield patterns of the 4 MHz system. The dipole-like farfield patterns contain large nulls at 0° and 180° in azimuth, as seen in Fig 3 modes 13 and 14, corresponding to the larger estimation errors.

The azimuth estimation errors for an 11 MHz incident field using 16, 8, and 4 modes are shown in Fig 7. The azimuth errors for 16 and 8 modes were similar and both cases resulted in less estimation error than the corresponding results for the 4 MHz system. For the 11 MHz incident field, the estimation errors increase significantly when the number of modes is reduced to four, compared to both the 16 and 8 mode results of the 4 MHz simulation. The standard deviation of the estimation error shows the results of the 11 MHz AOA estimation to be

Figure 6. Comparison of the error standard deviation using 16, 8, and 4 modes for a 4 MHz incident field

Figure 8. Comparison of the error standard deviation using 16, 8, and 4 modes for an 11 MHz incident field

Figure 7. Comparison of the azimuth estimation error generated by 16, 8, and 4 modes for an 11 MHz incident field

Figure 9. Error standard deviation for an array of four randomly chosen modes which produce the lowest standard deviation of azimuth AOA error for the 4 MHz system. Results compared to the mean standard deviation of 25 random configurations and the four mode configuration with highest input impedance

unreliable when using the four modes with the highest input impedance, as seen in Fig 8.

The four modes used to generate the results shown in Figures 6 and 8 were chosen based upon the maximum input impedance of the feeds used to excite the modes, which corresponded to modes with the largest directive gain. To determine if the performance of the four-mode systems could be improved using other mode combinations, 25 different random combinations of four modes were simulated for both the 4 MHz and the 11 MHz systems, as discussed in the previous section. The results for the configuration producing the lowest standard deviations of azimuth estimation error for the 4 MHz system are shown in Fig 9. Similarly, the results for the four-mode configuration producing the lowest standard deviation of error for the 11 MHz system are shown in Fig 10. These results indicated that that the maximum input feed impedances significantly affect estimation error, as expected. The random configuration producing the best performance was also the random configuration consisting of the four modes with highest input impedance for both the 4 MHz and 11

MHz simulation.

The location of the feed points for the four mode configuration with the highest directive gain for 4 MHz are shown on the plate model in Fig 11. Similarly, the location of the feed points for the four highestet directive gain modes for 11 MHz are shown on the plate model in Fig 12. The location of the feed points indicate that the farfield patterns of the modes as well as the spatial diversity play a significant role in reducing the amount of azimuth AOA estimation error in an amplitude comparison system such as MLM. The farfield patterns depend on the input impedance of the feeds, as well as, the relative locations of the feedpoints. The location of the feeds for the 11 MHz systems in Fig 12 appear to be very close and the farfield patterns in Fig 4 show that the farfield patterns for feeds 11 and 12 are very similar, as are the patterns for feeds 13 and 16. The phase relationship between these feeds are not shown but are nearly orthogonal.

Figure 10. Error standard deviation for an array of four randomly chosen modes which produce the lowest standard deviation of azimuth AOA error for the 11 MHz system. Results compared to the mean standard deviation of 25 random configurations and the four mode configuration with highest input impedance

Figure 11. Feed point locations resulting in lowest standard deviation of error for four modes with highest input impedance at 4 MHz.

IV. CONCLUSION

Airborne AOA estimation of a HF signal is challenging because the dimensions of the platform are roughly on the order of the signal wavelength, and sometimes less than one wavelength. This relative size eliminates the use of linear antenna arrays with half-wavelength spacing, as is traditionally used for beamforming AOA systems. One potential method for performing AOA estimation from an airborne platform is to use the structure itself as the array, a concept that has been explored since the 1950s. The challenge is to determine the minimum number of modes required to accurately estimate AOA.

This paper examined the performance of an AOA system comprised of a maximum of 16 modes on a two-dimensional platform. The MLM algorithm was used to estimate azimuth AOA. Two frequencies were used, 4 MHz and 11 MHz, due to the relative size of the wavelengths compared to the platform

Figure 12. Feed point locations resulting in lowest standard deviation of error for four modes with highest input impedance at 11 MHz.

dimensions. The results of the simulations showed that the number of modes impacted AOA estimation error more as the size of the platform increased relative to the wavelength of the signal of interest, i.e. four modes resulted in more estimation error for the 11 MHz system. For both systems, more modes produce less estimation error.

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