Deformation and Vibration of Conformal Antenna Arrays and Compensation Techniques

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ABSTRACT

Conformal antenna arrays fitted to the surface of a non-planar part of modern aircrafts, vehicles or ships are considered an attractive alternative for certain applications where planar arrays or reflector antennas have definite drawbacks. Some of the potential advantages are improved aerodynamics, increased payload, large field of view (LFOV) and low observability. The occurrence of static and dynamic deformations can have a severe impact on the performance of conformal antennas on aircrafts and other vehicles. Therefore it is essential to study the different deformation and vibration mechanisms and their influence on the antenna system.

The present paper gives an overview over different tools for the electromagnetic modelling and design of conformal array antennas. A method for the passive compensation of static deformations and vibrations based on the estimation of the elements' position and the deformed array shape will be presented. Examples of the numerical analysis of conformal array geometries with deformations and the resulting effects on the system (i.e. antenna parameters such as beam width, sidelobe level, pointing error etc.) will be shown.

1.0   INTRODUCTION

Applications of conformal array antennas are of growing interest in modern RADAR and communications systems. Depending on the shape of the aperture, conformal antenna arrays fitted to the surface of a non-planar part of aircrafts, vehicles or ships can have advantages such as large field of view (LFOV), improved aerodynamic behaviour, reduced space requirement and low observability (LO). However, the usage of conformal array technology in commercial applications is still comparably rare and the technology needed for fabrication, assembly and feeding of flush mounted antenna elements on single or double curved surfaces is still in its infancy.

A problem that both planar and conformal antenna arrays on aircrafts and other vehicles are facing is the occurrence of static deformations and vibrations which can have a severe impact on the performance of the antenna and the underlying system. The deformations and vibrations may be caused by inertial forces and aerodynamic loads. The distortion of the antenna surface may influence the antenna's radiation pattern and cause errors such as bore sight errors and increased side lobe levels. The effects of static deformations and dynamic vibrations on antenna performance as well as different techniques for compensation are studied in the scope of a NATO Research Task Group [1].

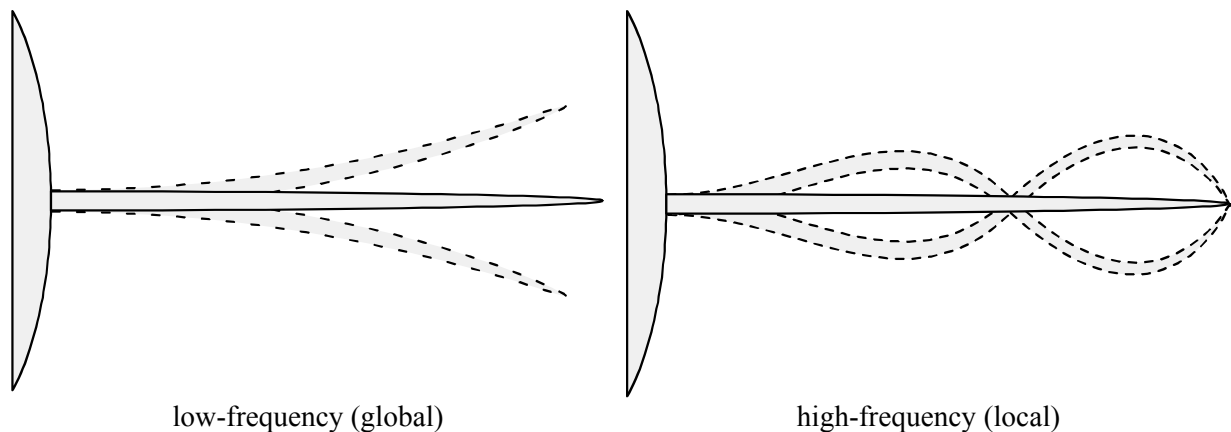low-frequency (global)   high-frequency (local)

Figure 1: Effects of different vibration modes on the wing of an aircraft.

In order to assess the levels of distortion and potential effects, it is of importance to develop computational modelling tools and to conduct studies on the occurrence of vibrations for the aircraft/vehicle platform of interest to provide knowledge

- about the size of steady and unsteady aerodynamic loads at the antenna locations,

- about amplitudes and frequencies of vibrations of the antenna surface and the surrounding aircraft structure,

- about the eigenfrequencies and vibration modes of the unloaded aircraft structure (at the locations of the antennas) and the magnitude of local steady displacements,

- about effects of vibrations on performance of conformal antennas.

Depending on the mechanical properties of the structure and the actual load profile (i.e. force and frequency of excitation), different structural eigenmodes at different eigenfrequencies may be excited. Figure 1 illustrates the effects of vibration at different frequencies on the wing of an aircraft. While the lower-frequency modes result in a *global* deformation of the shape (the object is mainly shifted or tilted), the higher frequency modes cause a deformation of the shape itself and a change of the *local* environment within certain regions. The effects are shifting and tilting as well as a de-orientation of the antenna elements, if present.

The effects of deformation and vibration may be prevented or at least alleviated by mechanical measures such as reinforcement, active or passive damping, or even active shape control on global or local level. While these implementations of such methods is comparably extensive and a large amount of control is required, compensation techniques by means of signal processing are also feasible. The present paper investigates the effects of static deformations and vibrations on a generic antenna array and describes a technique for compensation based on estimation of the deformed array aperture using a snapshot of received complex signals.

2.0 THEORY

Electromagnetic modelling and design of non-planar antenna arrays is a much more complex task than for their planar counterparts because analytical refinement and array periodicity can not generally be used to simplify the physical relations. Several numerical methods can be applied to arrays of arbitrary shape but calculations are restricted to few array elements only due to limitations of the numeric performance of today's computers. An antenna array model based on the use of simple polarimetric antenna elements which can be described analytically was presented earlier [2]. It allows for the approximate calculation of

important electromagnetic parameters of small arrays including mutual coupling effects. This antenna model has been applied to the problem of a deformed antenna array aperture. However, mutual coupling has been neglected in the scope of the present study for simplification and to put emphasis on the effects of vibration.

2.1   Conformal Antenna Array Modelling

Consider the general case of an array of *N* antenna elements as shown in figure 2. The shape of the aperture and the orientation of the antenna elements may be arbitrary. In the receiving case, a number of *M* signals represented by plane waves are incident upon the antenna and the resulting voltages at the terminals of the *i*-th antenna element are given by

$$U_i = \sum_m \vec{l}_i(\vartheta_m, \varphi_m) \cdot \vec{E}_m \cdot e^{-j\vec{k}_m \cdot \vec{x}_i} \tag{1}$$

where $\vec{E}_m$ is the complex electric field vector representing strength, phase and polarisation of the *m*-th incoming signal, $\vec{k}_m$ is the wave number vector in the direction of signal *m*

$$\vec{k}_m = \frac{2\pi}{\lambda_0} \cdot \begin{pmatrix} \sin\vartheta_m \cdot \cos\varphi_m \\ \sin\vartheta_m \cdot \sin\varphi_m \\ {'}\cos\vartheta_m \end{pmatrix} \tag{2}$$

$\vec{x}_i$ is the antenna element's location and $\vec{l}_i$ is the vector effective length of the *i*-th antenna for the particular direction (ϑ_m, φ_m) representing the embedded antenna element pattern. Variations due to varying antenna type, location or orientation of the elements or mutual coupling are included in different functions of l_i.
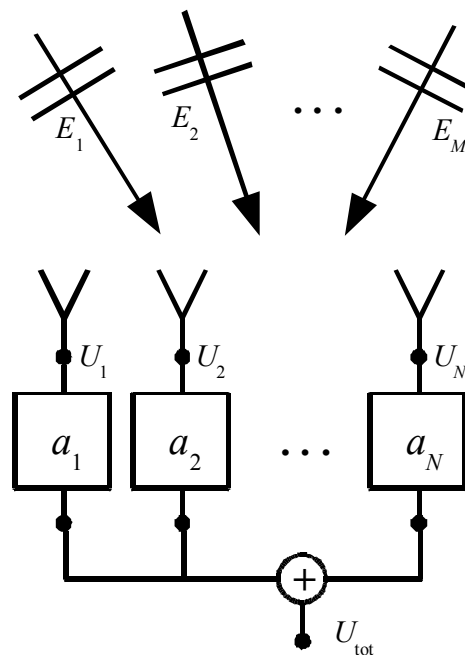
Figure 2: Illustration of an antenna array and multiple incoming signals.

The array pattern may be written as the sum of the received voltages multiplied by a given set of complex weights a_i for each antenna element:

$$U_{tot} = \sum_i a_i \cdot U_i \qquad (3)$$

For compensation of phase errors due to a deformed array shape, it is essential to have knowledge not only of the sum signal U_{tot} but on the complex amplitude U_i at the output of each antenna element. In a digital beam forming (DBF) system as shown in figure 3, the received signal is digitised in an early stage of the receive branch of each channel and the following steps, like low-pass filtering, complex multiplication with array weights, summation etc. may be accomplished in the digital domain. Provided that the numerical performance of the array processor is sufficient, such a system allows for several operations on the same set of received signals: Applying different sets of array weights for different frequencies or look angles as well as adaptive nulling in the presence of interference. In the following sections, digital beam forming and knowledge of the complex amplitudes at element level are presumed.
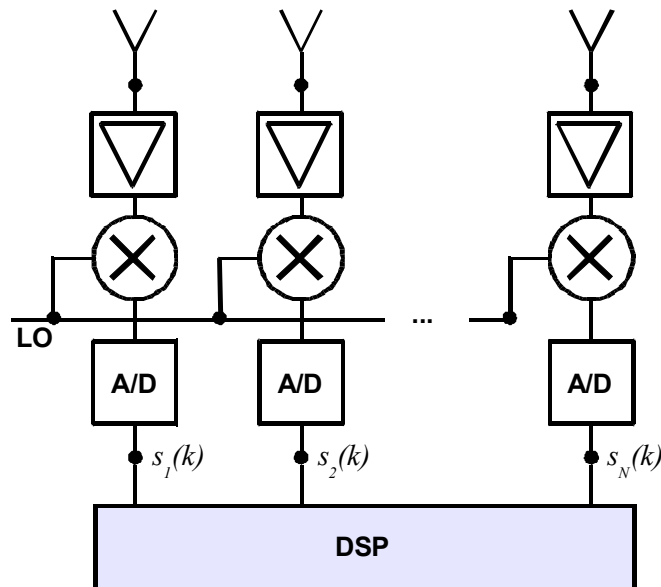

Figure 3: General layout of a digital beam forming antenna array in the receiving case.

2.2   Compensation of Deformations and Vibrations

Static deformations caused by mechanical damage or vibrations lead to a displacement and sometimes de-orientation of the antenna elements, depending on the type and frequency of excited structural eigenmodes. These changes may cause inaccurate signal levels or phase shifts and can influence the array sum pattern and overall performance of the system. Figure 4 shows an antenna array with a deformed aperture where an element is displaced a certain distance d along its antenna axis (normal to the aperture surface).
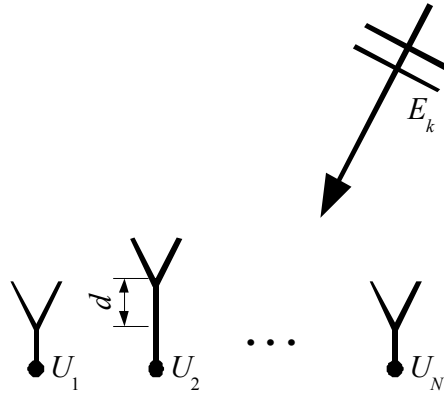
Figure 4: Plane wave incident upon antenna array with deformed shape.

In contrast to the undeformed case given in equation (1), the voltages at the antenna terminals may now be written as

$$U_i = \sum_m \vec{l}_i(\vartheta_m, \varphi_m) \cdot \vec{E}_m \cdot e^{-j\vec{k}_m \cdot (\vec{x}_i + d_i \vec{n}_i)} \qquad (4)$$

where $\vec{n}_i$ is the normal vector of the aperture at the element's position and d_i is the displacement of the i-th antenna element in the direction of $\vec{n}_i$. To avoid ambiguousness it is first assumed that the length of the displacement is smaller than half a wavelength (limiting the resulting phase shift to $\pm180°$) and the displacement is along the normal vector only, thus neglecting any de-orientation.

If the embedded element patterns $\vec{l}_i$ are known, the directions $\vec{k}_m$ can be estimated from a received set of complex voltages U_i using direction of arrival (DOA) estimation techniques (e.g. monopulse) or superresolution algorithms [3]. In the following examples, the Maximum Likelihood Estimation (MLE) has been applied [4].

Once the parameters of the incoming signals are known, the displacements d_i may be calculated from the difference between the actual phases U_i and the theoretical phases in the undeformed case $\Delta\varphi_i$. If only one incoming signal is present ($M = 1$), the solution is trivial:

$$e^{j\Delta\varphi_i} = e^{-j\vec{k}_1 \cdot (d_i \vec{n}_i)} \qquad (5)$$

In this equation it can be seen that the position may only be estimated where significant phase shifts due to the displacement occur. The direction normal to the angle of incidence (ϑ_m, φ_m) cannot be considered because a displacement in this direction does not result in any phase error. Thus, these angles have to be excluded from the compensation. The problem may be overcome in the case of multiple signals but the displacements must then be derived from equation (4) using a numerical solution for the linear system of equations, e.g. a least mean squares (LMS) algorithm. The technique may also be expanded for the broadband case of multiple incoming signals at different frequencies.

Because the patterns of the antenna elements are assumed to remain constant, changes of mutual coupling caused by changes in the antenna element environment as a result of deformations are not assessed. The phase ambiguity and the resulting limitation of small displacements ($\pm \lambda/2$) may be overcome by "unwrapping" the phases: In a regularly spaced array it is sufficient to postulate that the distance *between*

neighbouring elements and thus the phase shift due to displacement is limited but not the absolute value. An example of reconstructed phase angles for displacements larger than half a wavelength is shown in figure 5.
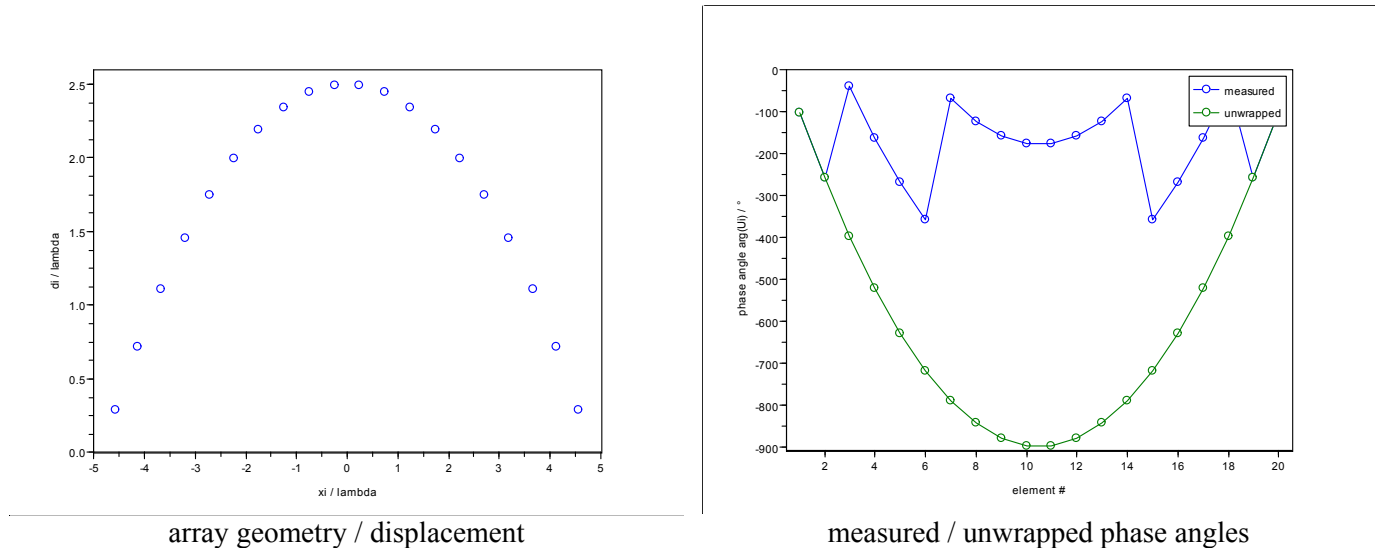
| array geometry / displacement | measured / unwrapped phase angles |

Figure 5: Reconstruction of phase angles for large displacements.

In the compensation technique described above the parameters of incoming signals are estimated from the receiving channels while the deformations are already present. The phase errors which are to be compensated as a result of the procedure will influence the accuracy of the estimated angles of arrival. It is therefore conceivable to expand the technique in an iterative way such that the phase shifts are corrected according to the results of a previous step and then used again for parameter estimation to give refined results.

3.0   NUMERICAL EXAMPLES

To illustrate its usage, the compensation technique described above has been applied to the 2-dimensional case of a uniform linear antenna array (ULA) and a conformal array in the shape of a circular sector. Canonical antenna geometries have been chosen, because structural eigenmodes may be calculated analytically [5]. The corresponding eigenfrequencies are dependent on the mass and stiffness of the used materials and are neglected in the scope of this study. The type of deformations, i.e. the amplitude and order of excited modes, that can be expected in a real environment strongly depend on the type of mechanical load (e.g. steady / unsteady) [6]. Here, the case that only one dominant low order (low frequency) mode or a number of high order modes are excited is investigated.

In the following examples, the antenna elements are considered to be isotropic point sources. It is assumed that only one incoming signal is present at an angle of $\varphi_1 = +60°$ and that the vibrations are quasi-static. In the case of time varying vibrations this means that the shape is assumed to remain constant for the processing time of a single compensation step.

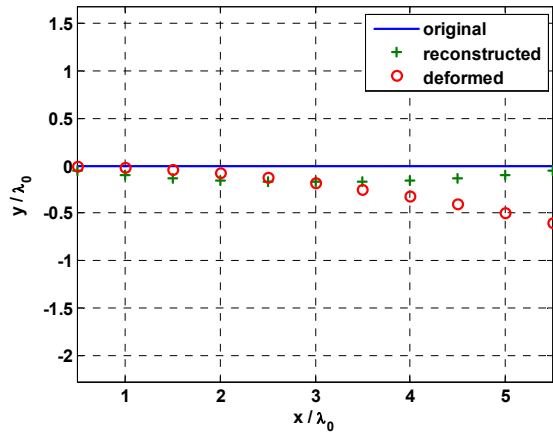### 3.1   Uniform Linear Antenna Array

The geometry of the linear array consisting of $N = 11$ antenna elements is shown in figure 6a. The array spacing is 0.5λ at the frequency of interest in the undeformed case. In the first example, it is assumed that the structure is fixed at the left hand side of the antenna and that the first structural eigenmode (similar to

the flapping of an aircraft wing) is excited with a maximum amplitude of $|d_{max}| = 0.6\lambda$. The deformed positions of the antenna at maximum deflection are also shown in figure 6a. The compensation method described above is now applied using the resulting complex voltages at the antenna terminals as received in the case of the deformation. From the calculated displacements, the actual positions of the elements are estimated. It can be seen in figure 6a that the deformed shape is not properly reconstructed mainly because the main effect in this example is a rotation of the whole antenna around the fixed point. The result is a pointing error of the DOA estimation (62° instead of 60°) which leads to an erroneous estimation of the displacements. However, the corrected phase shifts will result in a far field pattern pointing in right direction.

The phase distribution $arg(U_i)$ for all elements is shown in figure 6c for the case of the original undeformed shape, the deformed shape without any compensation and the corrected phases taking into account the estimated element displacements. As an example, the effect of the deformation on the antenna pattern scanned to the direction of the received signal is given in figure 6e. In the undeformed case, the selected array excitation coefficients are to add coherently for the given angle of incidence and produce a far field pattern of maximum directivity with a side lobe level of –13 dB. In the deformed case, the resulting normalised array far field pattern exhibits a pointing error of approx. 2° without compensation. The original direction of the main lobe is restored after compensation using the phase correction. Apart from a slightly increased side lobe level both the original and reconstructed patterns are almost identical.

In a second example, a random distribution of higher order vibration modes is excited, resulting in a more erratic distribution of the antenna elements. The maximum amplitude of the displacements is $|d_{max}| = 0.3\lambda$, a comparison between the original and the deformed shape as well as the estimated displacements is shown in figure 6b. Because the resulting phase variations are unambiguous in this case, the elements' positions are now properly calculated. The phase distribution in all three cases is given in figure 6d, the resulting array patterns are in figure 6f.
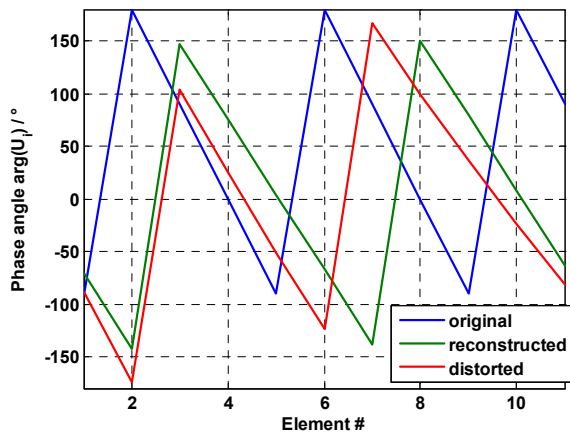
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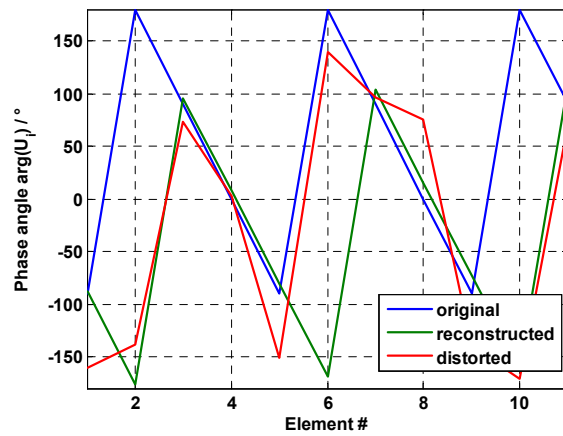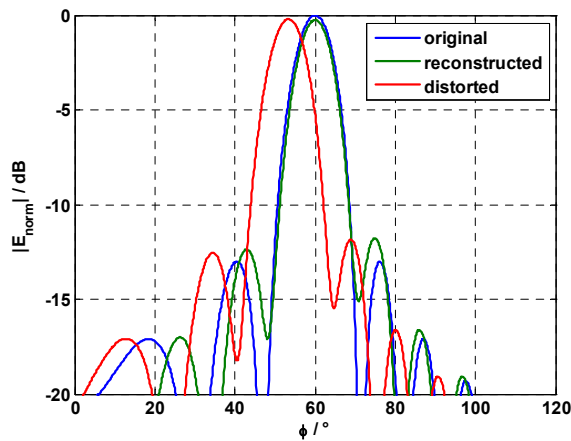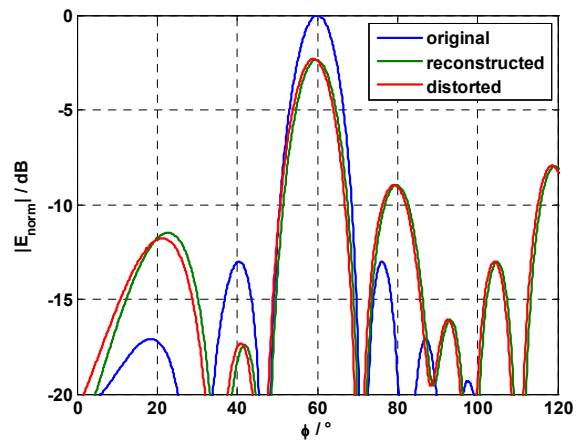Antenna Arrays and Compensation Techniques**
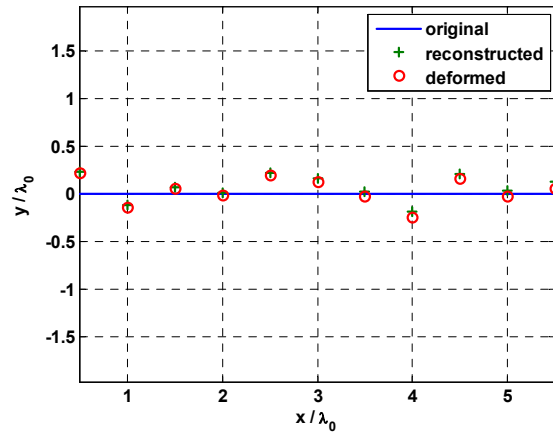
**Figure 6: Uniform linear antenna array – element positions, received
signal phase shifts and normalised array far field patterns.**

3.2 Cylindrical Antenna Array

The same scenario (one incoming signal at an angle of $\varphi_1 = +60°$) is investigated in the case of a circular sector array with N=31 antenna elements, a regular array spacing of 0.5λ and an opening angle of 180° (corresponding to an array radius of approx. 4.3λ) at the frequency of interest. The antenna is now assumed to be fixed at both ends. A structural eigenmode of lower order is excited, the results are shown in figures 7a, 7c, and 7e. Similar to the previous example of a ULA, the displaced elements' positions cannot always be calculated correctly, especially in the direction normal to the angle of incidence. To avoid this error, the affected area of the antenna array may be excluded from the procedure. It is shown in figure 7e that the deformation again results in a pointing error which can be corrected using the compensated phase shifts.

In the case of higher order vibration modes (figures 7b, 7d, and 7f), the effects are similar to the previous case: The deformation does not cause a pointing error in the array far field but a pattern degradation with increased side lobe levels. Although the displacements and thus the deformed antenna element positions are estimated very accurately, the compensated phase distribution does not improve the array far field significantly.

**Deformation and Vibration of Conformal
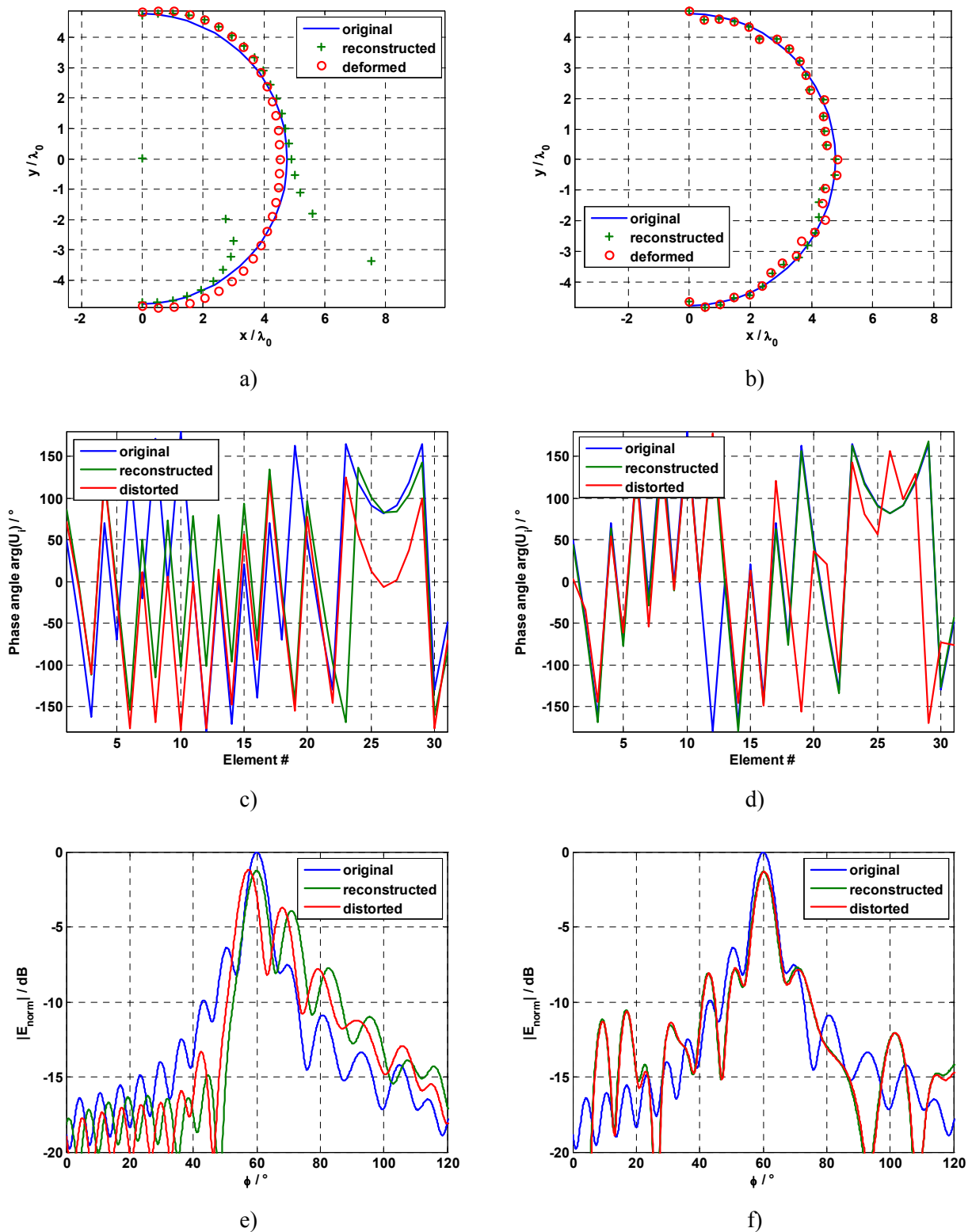Antenna Arrays and Compensation Techniques**

**Figure 7: Circular sector antenna array – element positions, received
signal phase shifts and normalised array far field patterns.**

4.0 CONCLUSIONS

The effects of static deformations and vibrations on the array far field of antenna arrays have been discussed. The results of lower order (global) and higher order (local) modes of vibration have been demonstrated in the case of a linear and a circular antenna array. In addition, a method for estimating the deformed antenna array shape and calculating corrected phase shifts has been introduced and simulation examples have been shown. According to these preliminary results, static deformations and vibrations may have significant influence on system performance. In many cases, compensation of phase errors is possible as shown in the scope of this study. In was possible in both the presented cases, to compensate for the effects of low-order vibration modes (pointing error). For high-order modes, however, the method did not have an effect. This problem will be subject of future work.

To apply this method in a real system, it is mandatory that all embedded antenna element patterns are known *a priori*. This may cause a disproportionately high effort for array calibration. Also, the extra numerical load for DOA estimation, phase correction and recalculating the sum signal may not be applicable in the case of real-time systems.

Since the simulation results are based on arrays of isotropic elements, it is planned to apply similar problems in the case of embedded far field patterns of real antennas from experimental data. The performance of superresolution algorithms in this context and application of an iterative process comprising multiple steps of refinement will also be investigated in the future.

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SYMPOSIA DISCUSSION – PAPER NO: 19

Author's Name: P. Knott

Question (D. Beckers):
Have you already studied or do you have an idea about the performance of the compensation technique for different patterns?

Author's Response:
So far, only some patterns have been studied.

Question (M. Banks):
What are the issues in going into more than one wavelength?

Author's Response:
The assumption is that the displacement is small compared to wavelength between <u>neighbouring</u> elements. It can be larger for larger areas of the array.

Question (B. Baron):
Is the solution numerically intense? How will it limit the size of the array that could be used?

Author's Response:
The numerical complexity of the method is in general that of DOA estimation. In the special case of ML-estimation it is a matrix – vector product where a dimension of the matrix is the number of antenna elements. This might be a limiting factor in the case of large arrays.

Question (H. Schippers):
What kind of application do you have in mind for your compensation techniques?

Author's Response:
So far, only system studies on antenna performance and compensation techniques have been conducted. In the future, it is planned to investigate the impact on SAR systems because the effects of vibrations seem to be significant.