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***Abstract*— Smart antenna technology can be applied for compensation of phase errors in digital airborne data communication when directional antenna arrays are installed on vibrating wing structures. The key elements of the smart technology are a real-time measurement system for the phase errors related to position errors of the antenna elements and a real-time adaptive phase-shifting system for the compensation of the phase errors.**

***Index Terms*— aircraft antennas , antenna arrays , array signal processing , data communication , digital communication , phase measurement**

I. INTRODUCTION

Wireless communication on board aircraft and Unmanned Aerial Vehicles is a prerequisite these days. Communication links have to provide pilots with all relevant information, and data links are required to guide Unmanned Aerial Vehicles through the airspace. Airborne platforms can also be used as a node or as a relay station in wireless communication architecture. For instance, they can be used for communication in military battle fields [1] and for restoring wireless communications in catastrophic events like the Tsunamis in Indonesia and Japan, or after the Hurricane Katrina in the USA (see [2] and [3]). The airborne communication requires the usage of directional array antennas to steer the antenna in a specific direction. For instance, in space in the direction of a satellite or to earth in the direction of the service area. Directional steerable antennas require wide aperture and sufficient space for installation. On Unmanned Aerial Vehicles there is not much space left for the installation of steerable antennas. The structural integration of antenna apertures in non-traditional locations (e.g., doors, wing skins, and fuselage panels) will greatly increase the available surface on air vehicles. However, when electronically steerable antennas are integrated into light weight structures of air vehicles, they are subject to unsteady aerodynamic loads. Mechanical forces and these aerodynamic loads will cause deformation of the supporting structure of the antenna array, which degrades the antenna performance. The aim of this paper is to demonstrate that smart antenna technology can re-establish the antenna radiation characteristics and can improve the quality of data communication when directional antennas are installed on vibrating aerostructures. In real-time the phase errors due to displacement of the antenna elements can be measured and the beam of the array can be adapted accordingly.

II. DIRECTIONAL ARRAY ANTENNAS ON VIBRATING WINGS

The levels of the deformation of wings of aircraft and UAV's have been assessed in previous papers (See [4] and [5]). The aerodynamic excitation was modeled by the Von Karman gust spectrum. This spectrum is based on empirical data and depends on parameters representing: altitude, a reference RMS gust speed and a turbulence scale. It defines the number of occurrences of gust being expected within a given period of time for the specified parameters. The results of the dynamical analysis of a typical motor glider are presented in Figure 1 where the blue circles describe the non-deformed front view of the simplified aircraft model. The red dots represent the wing vertical displacements relative to the wing root due to a Von Karman gust response (displacement levels that are exceeded once per flight hour). The deflections are in the order of 75 cm once per hour. Notice that higher deflections are also possible, but they occur less frequently.

The use of an L-band or C-band communication antenna array on the wing of such a UAV will lead to deformation of the antenna array. The positions and orientations of the elements of the array antenna change with respect to each other. The relative phases of the respective signals feeding the antenna elements of the array will vary, and therefore the antenna radiation pattern is affected: the main beam direction can change and the beam width and/or side lobe levels can increase.

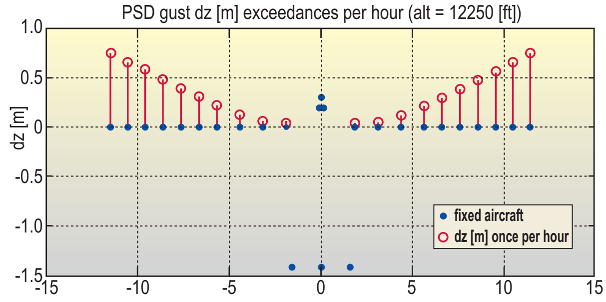


Figure 1 Assessment of wing deflection amplitudes for a typical motor glider

Figure 2 Vibrating plate with directional array antenna

III. DEMONSTRATION OF SMART ANTENNA TECHNOLOGY

For the verification of smart antenna technology a laboratory experiment has been set-up with the aim to demonstrate this technology to digital communication. The laboratory experiment has a vibrating plate with an 8x1 array of L-band patch antenna elements (see Figure 2). The plate has a fixture in the centre, which is attached to a shaker with vibration control software. On the ceiling of the room a transmit antenna has been positioned.

The present system architecture of the experimental set-up considers only data-communication in one direction (see Figure 6). The architecture contains a digital data transmission system and a receive antenna array with smart technology, which measures in real-time the phase errors due to displacement of the antenna elements and adapts in real-time the weights of the antenna array. The architecture for data communication via the vibrating antenna array was described in [6] and [7].

A. *Digital data communication*

The digital data transmission is performed by a commercial off-the-shelf AD8346 evaluation board of Analog Devices. In order to achieve high data rates and independence of the data link network a standard serial interface (RS-232) has been used to generate 2-PSK data. The serial interface signal has been adapted to the input specification of the modulator. The modulated signal is transmitted via a 1.81 GHz horn antenna at the ceiling.

For the receive part of the communication channel, the AD8347 board was applied as a demodulator. It is a silicon RFIC broadband direct quadrature demodulator with RF and baseband automatic gain control (AGC) amplifiers [8]. The RF input frequency ranges from 0.8 to 2.7 GHz. The output of the demodulator is amplified and connected to the receiving RS-232 serial interface.

B. *Receive Smart Antenna Array*

Due to vibrations of the plate the mutual positions of the antenna elements of the antenna array will change. This will introduce phase errors in the receiving antenna elements, which need to be compensated in real-time. This can be achieved by smart antenna technology which measures the phase errors and adapts the weights of the antenna array.

1) Phase measurement system

The phase errors are determined in real-time using the AD8302 Integrated Circuit of Analog Devices, appropriate dSPACE hardware and Matlab and Simulink software ([5],[9] and [10]). The horn antenna on the ceiling is used as transmit antenna. The patch antenna on the vibrating plate close to the fixture has been taken as reference element. The position of this element is assumed to be stationary at coordinate $\vec{r}_0$. The AD8302 Integrated Circuit measures the phase differences between this reference patch and the other patches. The principle of the phase measurement system is explained below.

Let the coordinates of the transmit antenna be given by $\vec{r}_T$. The electric field that is received on the reference antenna at position $\vec{r}_0$ is approximated by

$$E_0 = \frac{1}{4\pi\,|\vec{r}_0 - \vec{r}_T\,|} e^{-ik|\vec{r}_0 - \vec{r}_T|} \tag{1}$$

The electric field that is received on the measurement antenna at position $\vec{r}_m(t)$ follows from

$$E_m(t) = \frac{1}{4\pi\,|\vec{r}_m(t) - \vec{r}_T\,|} e^{-ik|\vec{r}_m(t) - \vec{r}_T|} \tag{2}$$

The AD8302 chip can detect the amplitude and phase of $E_m(t)/E_0$. Let

$$V_m(t) = E_m(t)/E_0 \tag{3}$$

The phase of $V_m(t)$ follows from $\arg(V_m(t))$. From (1) and (2) it follows that

$$\arg(V_m(t)) = k\,|\,\vec{r}_m(t) - \vec{r}_T\,| - k\,|\,\vec{r}_0 - \vec{r}_T\,| \tag{4}$$

The measurement of the phase error in the receiving antenna elements contains two steps. First, the calibration phase of $V_m(t)$ at antenna element *m* on the steady unperturbed plate is measured. The position of this element is denoted by $\vec{r}_m^{\,u}$. By equation (4) the calibration phase reads

$$\Phi_m^u = \arg(V_m) = k\,|\,\vec{r}_m^{\,u} - \vec{r}_T\,| - k\,|\,\vec{r}_0 - \vec{r}_T\,| \tag{5}$$

Next, the phase of $V_m(t)$ at antenna element *m* on the vibrating plate is measured. The only difference with respect to equation (5) is the position of the measurement antenna, which is now described by $\vec{r}_m^{\,p}(t)$ instead of $\vec{r}_m^{\,u}$. Hence, the detected phase of the perturbed measurement antenna becomes

$$\Phi_m^p(t) = \arg(V_m(t)) = k\,|\,\vec{r}_m^{\,p}(t) - \vec{r}_T\,| - k\,|\,\vec{r}_0(t) - \vec{r}_T\,| \quad (6)$$

Finally, the phase error in the receiving antenna element *m* follows from subtracting equations (5) and (6). The phase error becomes

$$\Delta\Phi_m(t) = \Phi_m^p(t) - \Phi_m^u \quad (7)$$

By equations (5) and (6) it follows that

$$\Delta\Phi_m(t) = k(|\,\vec{r}_m^{\,p}(t) - \vec{r}_T\,| - |\,\vec{r}_m^{\,u} - \vec{r}_T\,|) \quad (8)$$

In case the transmit antenna is far enough away from the vibrating antenna array, the phase error $\Delta\Phi_m(t)$ becomes

$$\Delta\Phi_m(t) = k(\hat{k}_m \bullet (\vec{r}_m^{\,p}(t) - \vec{r}_m^{\,u}(t)) \quad (9)$$

with $\hat{k}_m = (\vec{r}_m^{\,u} - \vec{r}_T)/\,|\,\vec{r}_m^{\,u} - \vec{r}_T\,|$. Equation (9) shows that the phase error $\Delta\Phi_m(t)$ is a measure for the displacement of antenna element *m* in the direction of the incident field.

From equation (7) it follows that it is essential first to measure the calibration phase difference Φ_m^u and then to measure in real time the phase differences $\Phi_m^p(t)$. In the laboratory experiment these phase differences are measured by the AD8302 Integrated Circuit of Analog Devices, appropriate dSPACE hardware, and Matlab and Simulink software ([5],[9] and [10]). The phase differences between the patch antennas are available in the digital domain. These measured phase differences are used to adapt in real time the weights of the beam forming system of the antenna array.

2) *Real-time adaptive beam forming*

The total electric field that is received by the antenna array on the vibrating plate is given by the summation of all fields multiplied by their excitations,

$$E_{tot}(t) = \sum\nolimits_m A_m E_m(t) \quad (10)$$

The excitations A_m are complex valued numbers. The modulus of A_m is used for tapering and the argument of A_m (related to the phase of the amplitude) for beam steering. The phase errors in the signal can be compensated by modifying instantaneously the argument of the excitations in equation (10) as follows

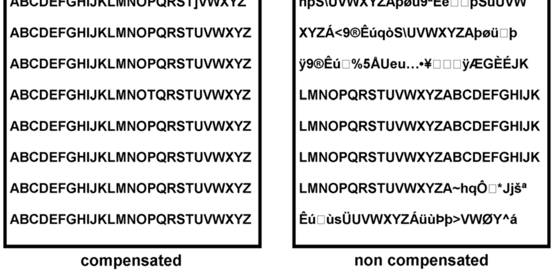
$$A_m := A_m e^{-i\Delta\Phi_m(t)} \quad (11)$$

When these excitations are applied in equation (10), the beam is in fact instantaneously steered. In the laboratory experiment the beam steering (indicated by Φ in Figure 6) has been implemented by using analogue phase shifters (type JSPHS-23+) for each channel. The phase measurement system measures phase differences between -180 and 180 degree. Hence the phase shifter should be capable to handle the same range. The available phase shifters (type JSPHS-23+) supplies a phase shift range of 250 degree at a frequency of 1.81 GHz. Therefore two phase shifters are placed in one chain to achieve the needed phase shift range. The control voltage range is 0-15V while the DAC supplies only 10 V. In order to be able to use the full range of phase shifts a level shift of the control voltage is needed. The combined signal of the beam former is amplified and sent to the AD8347 demodulator. The output of the demodulator is amplified and connected to the receiving RS232 serial interface.

The descriptions of the smart antenna architecture and modulation techniques for communication in the experimental set-up have been presented in [6]. The present paper describes the results of the communication link of the vibrating antenna system.

IV. RESULTS

A modulated signal is transmitted and received with a data rate of 112.5kBit/s with one stop and one start bit used for each byte. Hence for 8 bits data (one byte) 10 bits have to be transmitted. The frequency of the vibrating plate on the shaker is 3.78 Hz. The maximum deflection at the tip of the plate is 18 cm. Hence, the tip deflection is in the same order of magnitude as the wavelength of the L-band antenna elements on the plate. Different sound and text files have been transmitted. Figure 3 present some results of the repeated transmission of the alphabet over the communication link. Figure 4 shows transmission errors for a transmitted text file (16kByte). For the compensated case only a few errors occur whereas errors increase for the non-compensated case. In Figure 4 a line error is counted if one symbol in a line is corrupted. These figures show that the smart antenna technology almost completely repairs the errors.



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ABCDEFGHIJKLMNOPQRSTUVWXYZ
ABCDEFGHIJKLMNOPQRSTUVWXYZ
ABCDEFGHIJKLMNOPQRST]VWXYZ
ABCDEFGHIJKLMNOPQRSTUVWXYZ
ABCDEFGHIJKLMNOPQRSTUVWXYZ
ABCDEFGHIJKLMNOTQRSTUVWXYZ
ABCDEFGHIJKLMNOPQRSTUVWXYZ
ABCDEFGHIJKLMNOPQRSTUVWXYZ
ABCDEFGHIJKLMNOPQRSTUVWXYZ
ABCDEFGHIJKLMNOPQRSTUVWXYZ
```

compensated

```
LMNOPQRSTUVWXYZABüEÆGHIJK
LMNOPQRSTUVWXYZABè<þKÌMNOp
ñþS\UVWXYZÁþøü9ªÊê□□þSüUVW
XYZÁ<9®ÊúqòS\UVWXYZAþøü□þ
ÿ9®Êú□%5ÅUeu…•¥□□□ÿÆGÈÉJK
LMNOPQRSTUVWXYZABCDEFGHIJK
LMNOPQRSTUVWXYZABCDEFGHIJK
LMNOPQRSTUVWXYZABCDEFGHIJK
LMNOPQRSTUVWXYZA~hqÔ□*Jjšª
Êú□ùsÜUVWXYZÁüùÞþ>VWØY^á
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non compensated

Figure 3 Text file sent over data link (with and without real-time adaptive beam forming)

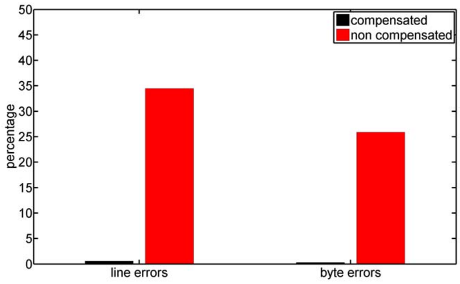

Figure 4 Line and byte errors for text file of 16kByte

The data communication link on the vibrating antenna has also been used to test sound files. Figure 5 illustrates the spectrum deformation for a pure 440 Hz tone. The red line in the figure reveals that the spectrum is broader and noisier when phase errors are not compensated. With the phase compensation network this effect is corrected.

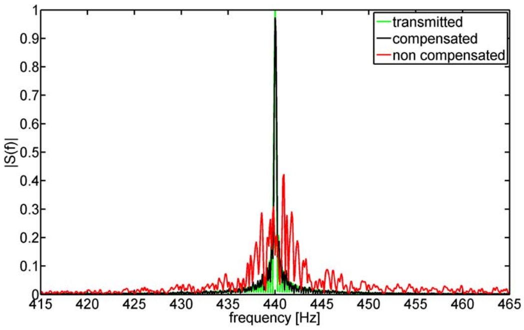

Figure 5 Spectrum of a 440 Hz tone in data link

V. CONCLUSIONS

A smart antenna-system has been developed for installation on light-weight aircraft structures which are subject to deformations and vibrations. The antenna contains two main units: one for real-time measurement of phase errors, and a second unit for real-time adaptive beam-forming by phase-shifters. The phase errors due to the displacement of the antenna patches are accurately measured and compensated by the beam-forming unit.

By means of simulations it has been shown in [6] and [7] that phase errors due to vibration of the antenna array also effect data transmission. Some pictures were digitized and modulated. Without real-time adaptive beam forming system the demodulation is not capable to resolve the symbols of the transmitted signal, and therefore the pictures are garbled. However, by means of the smart antenna technology as described in [6] and [7] the pictures can be corrected.

In the present paper the smart antenna technology has been used in a laboratory experiment. The aluminium plate with antenna array was put on a shaker with vibration control software. Digital data transmission over the link has been verified by using the array antenna without and with phase compensation. It has been shown that the quality of the transmitted audio signals was greatly improved by compensating phase errors by means of the implemented real-time adaptive beam-forming unit.

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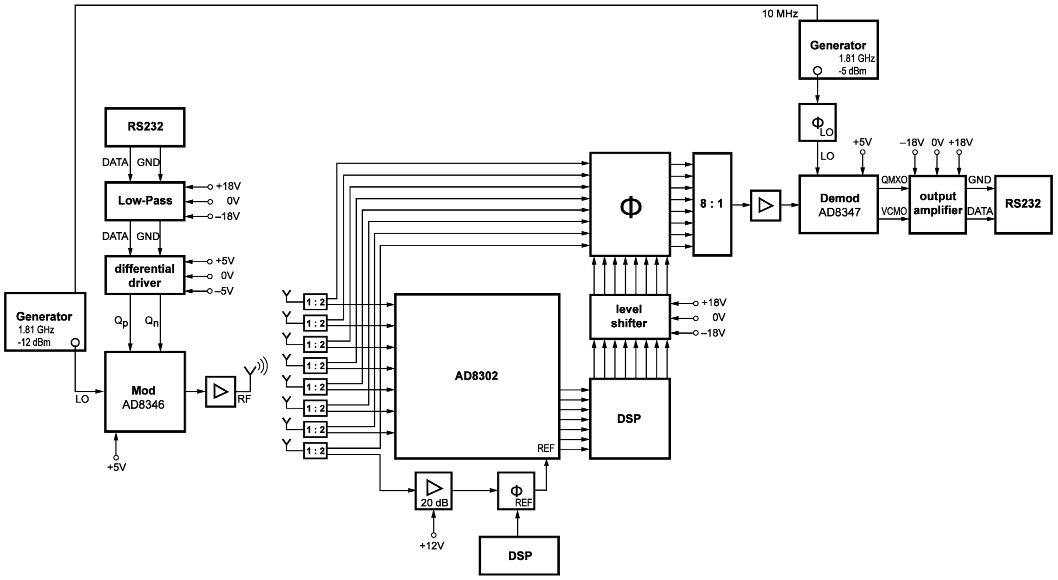

Figure 6 System architecture of real time adaptive beam forming system applied to data communication