

Defect Detection in ISC Cylinder using Spoof Plasmon Polaritons

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ABSTRACT

NASA is exploring the use of microwave Spoof Plasmon Polaritons (SPP) to detect defects in Integrally Stiffened Cylinders (ISC). This work investigates the detection of simulated defects in the form of aluminum wires to replicate manufacturing inclusions. These wires ranged in size from as small as 10 mm long and 3.1 mm dia. to 50 mm long 3.1 mm dia., placed between the stiffeners of an ISC. SPPs act as a chain of microwave cavity resonators where added metal changes the volume of the cavity. These changes manifest as changes in the electrical parameters (such as changes in the impedance) which can be measured by a vector network analyzer.

1 BACKGROUND

NASA's Advanced Air Transport Technology (AATT) project is exploring rapid manufacturing technologies for metallic fuselages. One technology is the flow forming of integrally stiffened cylinders (ISCs) to produce 3 m dia., 1.524 m long open cylinders with integral longitudinal blade stiffeners, which can be fabricated in ~1.5 hours [1]. To evaluate this technology, a fuselage manufacturing demonstration article (MDA) has been fabricated and delivered to NASA Langley Research Center (Fig. 1). One challenge associated with scaling up the flow forming process is the formation of defects during the forming process [2], such as inclusions or voids. Accordingly, accurate and high throughput defect detection could prove critical in reducing component inspection times. To achieve this goal, a novel technique using electromagnetic surface waves called spoof plasmon polaritons are being investigated for nondestructive evaluation (NDE) of metallic ISC structures.

Spoof Plasmon Polaritons (SPP) are electromagnetic surface waves that exhibit a non-radiative mode where the energy of the mode is concentrated at the interface, and it decays exponentially from the interface between a dielectric and a metal [3]. The SPPs act as a series chain of microwave cavity resonators. SPPs have been previously used for other applications in non-destructive testing (NDT). For instance, SPPs have been used to detect defects in 3D printed waveguides [4]. In another method SPPs have been used to detect voids in dielectric materials [5]. A flexible Spoof plasmonic device used a water filled tube to detect defects in non-metallic composites like PVC pipes [6]. The use of SPPs for detecting simulated defects added to a linear aluminum corrugated structure has been demonstrated [7].



Figure 1. 3 m diameter, 1.524 m long fuselage manufacturing demonstration article with stiffeners.

2 EXPERIMENTAL SETUP

The SPP system consists of a vector network analyzer which is connected to a horn antenna and a 31 mm long coaxial wire antenna. The test specimen is an ISC that is 3 m diameter and 1.524 m long. The stiffeners are 12.7 mm high and are spaced every 58.42 mm. The coaxial antenna is aligned vertically and is located in the center between the stiffeners. The simulated defects are placed 292.1 mm from the coaxial antenna. The horn antenna is set at a 45° angle and is located 432 mm from the coaxial antenna (Fig. 2).

The network analyzer raw data consists of 10001 points of magnitude and phase angle for the S_{21} scatter parameter across 1.817 GHz to 2.2 GHz. For this work, a data set is defined as the set of 10001 S_{21} coefficients collected across one frequency sweep. Each test run consists of 3 data sets. Each run starts and ends with a dataset without a simulated defect present while the second data set consists of a simulated defect placed 292.1 mm from the coaxial antenna.

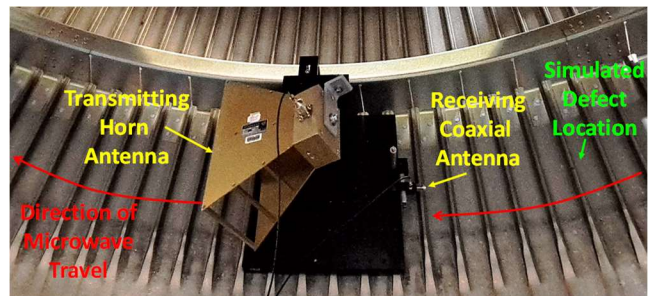


Figure 2. Test setup, ISC, Horn and coaxial antennas.

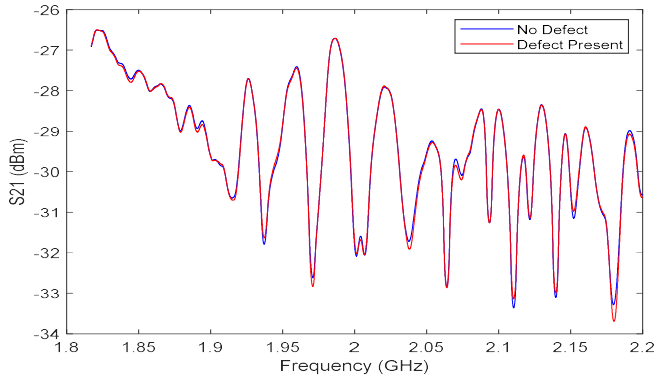


Fig. 3. The S_{21} log magnitude response of the ISC with and without a simulated defect.

To simulate defects, solid aluminum wires of lengths: 5, 10, 15, 25, and 50 mm were placed between the stiffeners of the test specimen. The wires are placed singly between the stiffeners to simulate an inclusion, fillet or other extra material remaining after fabrication. Aluminum was chosen to match the aluminum cylinder. Once the wires are in contact they act electrically the same as an inclusion. An example S_{21} log magnitude response for the case with and without a simulated defect is given in Fig. 3.

For this work, it was experimentally determined that the delta sum of the impedance response yields the lowest noise. First, the impedance was calculated from the S_{21} measurement using:

$$Z = Z_0 \frac{2(1 - S_{21})}{(S_{21})} \quad (1)$$

where Z_0 is 50 Ω . To highlight the variance in the defect states, the change or delta impedance for our measurements is calculated using the baseline subtraction method:

$$\Delta Z = Z_i - Z_{nd_i} \quad (2)$$

where Z_i is the current data set with or without a defect and Z_{nd_i} is the first data set without a defect. To develop a useful indication for detection of defects, a method of dimensionality reduction was needed. A simple summation of the delta impedance provides low noise, easily computed results. The summation of the delta impedance across 10001 points of a data set is given by:

$$SZ = \sum_{i=1}^{10001} (\Delta Z_i) \quad (3)$$

4 RESULTS

The sum of the delta impedance for each of the five simulated defects are given in Fig. 4. For each defect case, one data set with a defect and two data sets without a defect were taken. Note that the larger the defect volume, the larger the response. For all but the smallest defect (5 mm), the noise level without defects is lower than the amplitude for the defect case. Therefore, the smallest simulated defect that was detected with this limited dataset was 10 mm in length and 3.1 mm in diameter.

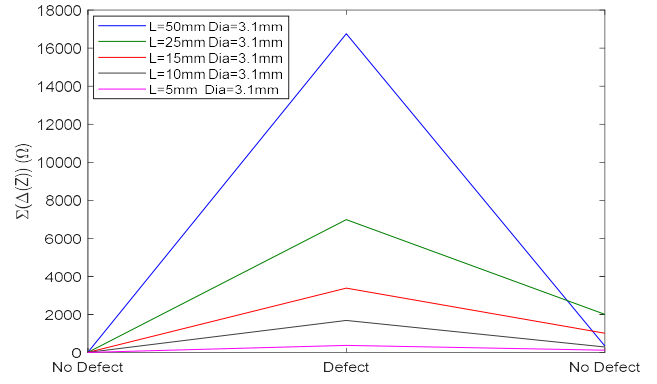


Figure 4. The sum of the delta impedance results with and without simulated defects.

CONCLUSIONS

The first use of spoof plasmon polaritons for defect detection in ISCs has been demonstrated using simulated defects (wires placed in between the stiffeners). The sum of the change in the impedance technique has been utilized as the indication for detecting the different sizes of simulated inclusions. This technique was used to detect a wire as small as 10 mm in length and 3.1 mm in diameter. Future work will investigate voids and cracks to determine if other defect types can be detected, as well as investigating limitations and optimization methods to find the smallest defects can be detected.

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