Interval Fuzzy Approach to Non-Destructive Testing of Aerospace Structures and to Mammography

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Aerospace testing: why. One of the most important characteristics of the plane is its weight: every pound shaved off the plane means a pound added to the carrying ability of this plane. As a result, planes are made as light as possible, with its "skin" as thin as possible. However, the thinner the layer, the more vulnerable is the resulting structure to stresses and faults, and a flight is a very stressful experience. Therefore, even minor faults in the plane's structure, if undetected, can be disastrous. To avoid possible catastrophic consequences, before the flight, we must thoroughly check the structural integrity of the plane.

Aerospace testing: how. Some faults, like cracks, holes, etc., are external, and can, therefore, be detected during the visual inspection. However, to detect internal faults (cracks, holes, etc.), we must somehow scan the inside of the thin plate that forms the skin of the plane. This skin is not transparent to light or to other electromagnetic radiation; very energetic radiation, e.g., X-rays or gamma-rays, can go through the metal, but it is difficult to use on such a huge object as a modern plane.

The one thing that easily penetrates the skin is vibration. Therefore, we can use sound, ultrasound, etc., to detect the faults. Usually, a wave easily glosses over obstacles whose size is smaller than its wavelength. Therefore, since we want to detect the smallest possible faults, we must choose the sound waves with the smallest possible wavelength, i.e., the largest possible frequency. This frequency is usually higher than the frequencies that we hear, so it corresponds to *ultrasound*.

Aerospace integrity testing is very time-consuming and expensive. One possibility is to have a point-by-point ultrasound testing, the so called *S-scan*. This testing detects the exact locations and shapes of all the faults. Its main drawback, however, is that since we need to cover every point, we get a very time-consuming (and therefore, very expensive) testing process.

A faster idea is to send waves through the material so that with each measurement, we will, be able to test not just a single point, but the entire line between the transmitter and the receiver. To make this procedure work, we need special signals called *Lamb waves*.

There are other testing techniques. All these techniques aim at determining whether there is a fault, and if there are faults, what is the location and the size of each fault.

How can we save time and money? In spite of many time-saving ideas, for each of these methods, we must still scan a huge area for potential small faults. As a result, testing requires lots of time, and is very expensive. How can we save the time and cost of testing? Our main idea is this:

The existing testing procedures are very expensive and time-consuming because they try not only to check whether there is a fault, but also to find its location and size. If our only goal is to detect the fault, and we are not interested in its exact location, then the problem becomes much simpler and hopefully, easier to solve. Therefore, we suggest to make a two-step testing:

- First, we apply a simpler test to check whether there is a fault.
- Only when the first test detects the presence of a fault, we run more expensive tests to locate and size this fault.

This two-step procedure is very similar to medical testing: In medical testing, first, the basic parameters are tested such as body temperature, blood pressure, pulse, etc. If everything is OK, then the person is considered healthy. Only if something is not OK, then the whole battery of often expensive and time-consuming tests is used to detect what exactly is wrong with the patient.

So the question is: How can we detect the presence of a fault?

Our main idea. Let us first describe this idea in general terms. For testing, we send a signal and measure the resulting signal. The input signal can be described by its intensity $x_1, \ldots, x_n$ at different moments of time. The intensities $y_1, \ldots, y_m$ of the resulting signal depend on x_i: $y_j = f_j(x_1, \ldots, x_n)$, where the functions f_j depend on the tested structure.

Usually, we do not know the exact analytical expression for the dependency f_j, so we can use the fact that an arbitrary continuous function can be approximated by a polynomial (of a sufficiently large order). Thus, we can take a structure, try a general linear dependency first, then, if necessary, general quadratic, etc., until we find the dependency that fits the desired data.

If a structure has no faults, then the surface is usually smooth. As a result, the dependency f_j is also smooth; we can expand it in Taylor series. Since we are sending relatively weak signals x_i (strong signals can damage the plane), we can neglect quadratic terms and only consider linear terms in these series; thus, the dependency will be *linear*.

A fault is, usually, a violation of smoothness (e.g., a crack). Thus, if there is a fault, the structure stops being smooth; hence, the function f_j stops being smooth, and therefore, linear terms are no longer sufficient. Thus, *in the absence of fault, the dependence is linear, but with the faults, the dependence is non-linear.* This theoretical conclusion was experimentally confirmed [1].

So, we can detect the fault by checking whether the dependency between y_j and x_i is linear.

Interval methods are needed. After K measurements, we have K sets of data $\tilde{x}_1^{(k)}, \ldots, \tilde{x}_n^{(k)}, \tilde{y}_1^{(k)}, \ldots, \tilde{y}_m^{(k)}$, $1 \le k \le K$. Usually, we do not know the probabilities of different measurement errors, we only know the upper bounds for these errors. So, we know the *intervals* $X_1^{(k)}, \ldots, X_n^{(k)}, Y_1^{(k)}, \ldots, Y_m^{(k)}$ of possible values of the measured quantities. We want to check whether this dependence can be linear, i.e., whether these exist coefficients c_{ij} for which, for every k and j, $\sum c_{ij} \cdot x_j^{(k)} \in Y_j^{(k)}$ for some $x_i^{(k)} \in X_i^{(k)}$. This is a known problem of interval computations: check whether the given system of interval linear equations is solvable (here, the unknowns are c_{ij}, interval coefficients are $X_i^{(k)}$ and $Y_j^{(k)}$).

Our main concern is not to miss the fault, so we need *guaranteed* methods. Thus, we need to use interval (guaranteed) methods for solving linear interval systems.

Applications to mammography. The main problem of mammography is to detect small non-smoothnesses in the mammal (small clots, cracks, etc.), which may indicate a tumor. When formulated in these terms, the problem sounds very similar to the problem of aerospace testing: in both cases, we must detect possible non-smoothness. Thus, we can use the above idea in mammography as well: if the dependence is linear, everything is OK, else further testing is needed.

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