ANALYSIS OF NONLINEAR EFFECTS IN DIAGNOSTICS OF COMPOSITE STRUCTURES

Jacek DZIURDŹ[1], Wojciech SKÓRSKI[2]

[1]Institute of Machine Design Fundamentals, Warsaw University of Technology
Narbutta str. 84, 02-524 Warszawa, jdz@simr.pw.edu.pl
[2]The Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology
Nowowiejska str. 22, 00-655 Warszawa, wskor@meil.pw.edu.pl

Summary

The following text presents possibilities of the analysis of nonlinear effects in research of high-durability of carbon fibre composites, on the example of the sailing ship mast. The special attention was returned on the possibility using of modern techniques of measurement deformations with optical fibre sensor with the change of the light wavelength – Fibre Bragg Grating. Analyse the diagnostic problem of condition in consequence dynamics analysis of composite structure.

Keywords: nonlinear effects, diagnostic, carbon fibre composite, Fiber Bragg Grating.

ANALIZA ZJAWISK NIELINIOWYCH W DIAGNOZOWANIU KONSTRUKCJI KOMPOZYTOWYCH

Streszczenie

Tekst przedstawia możliwości analizy zjawisk nieliniowych w badaniach dynamiki wysokowytrzymałych struktur z kompozytów węglowych, na przykładzie masztu jachtu żaglowego. Szczególną uwagę zwrócono na możliwość wykorzystania nowoczesnych technik pomiarów odkształceń z czujnikami światłowodowymi ze zmianą długości fali świetlnej – siatki Bragga. Przeanalizowano problem diagnozowania stanu na podstawie analizy dynamiki konstrukcji kompozytowych.

Słowa kluczowe: zjawiska nieliniowe, diagnostyka, kompozyt węglowe, światłowodowe siatki Bragga.

1. INTRODUCTION

Constantly increasing progress in such fields as e.g. chemistry and material engineering, supported additionally by technological potential, is the reason that new materials are appearing in the market. Machine elements made of them are characterised by structural properties significantly different than elements made of "traditional" materials.

There are certain fields completely dominated by, we can even say limited to, the application of composite materials. Typical example is production of equipment for highly competitive sports. Now-a-days composites dominated motoring, gliding and yachting, in the field of small vessels (yachts, motorboats, and amagnetic war-ships), where they are mainly applied for monocoque structures (hulls, fuselages, wings and elements of furnishing). Significant progress, which can be described as being of a revolutionary character, was caused by an introduction of carbon fibres as a reinforcement.

Carbon composites are materials, which can have all strength parameters significantly better than alloy steels (generally metals) at smaller masses (in contrast to other kinds of composites).

In point of fact, composites are not *sensu stricte* "materials" in a purely engineering meaning. A structure obtains its proper material properties after a final shaping and every further modification, if it is possible at all, only those properties deteriorates. Therefore we can rather say about a composite structure and not a constructional material. Even in the simplest case (beam, outrigger etc.) a structure is:

- anisotropic in a relatively wide range, which depends on the production technology,
- non-linear for elastic influences and composition of stresses,
- practically not undergoing corrosion (a positive aspect) only environment erosion, which causes its very long life and difficult utilization (a negative aspect),
- subject to a material fatigue in a way different than metals,
- unique in much wider range than the steel structure.

Repeatability of material parameters of composite structures requires an ideal repeatability of technological processes of a composite components production (fibres, fabrics) as well as of a composite structure. Thus, each composite structure is different and these differences are so pronounced that they are still subjects of serious scientific investigations – quite often the secret ones. A certain general rule can be found on the basis of now-a-days well developed "composite mechanics" [1], however, mathematical models are becoming very fast out of date in view of new technologies.

Typical element made of carbon composite is a mast of a sailing yacht. More and more attention is recently paid to a mast structure in an expectation of a further improvement of yacht performances. It might seem, that the designer gets a wide room for manoeuvre having at his disposal the newest designing methods and the cosmic era materials. However, he must confront problems related rather to incomplete theoretical description of the phenomenon or to impossibility of its strict solution.

Thus, there is a need of performing research of a structure dynamics - with non-linear effects taken into consideration.

2. NON-LINEAR EFFECTS IN DYNAMICS OF COMPOSITE MASTS

A problem of mechanical vibrations was practically not existing in the case of stiff wooden and metal masts. Its quite different for composite masts.

Vibrations of a system mast-rigging for the so-called "save" system enabling shaping – in a relatively wide range and at the minimal number of ropes - a static deflection compatible with aerodynamic requirements, is presented in Fig. 1 [2].

The basics of the problem constitute completely different relation between a mast stiffness and a rigging stiffness.

It can happen, for the composite mast, that the coefficient of elasticity of tight ropes lashing the modal point is higher than the coefficient of transverse stiffness of the span. In addition, surface vibrations occur in a thin mast shell propagating with various velocities in mutually perpendicular planes, since the mast cross-section is not round and a material is anisotropic. The effect, which might be called "cross-sectional vibrations", is presented in Figure 2 [2].

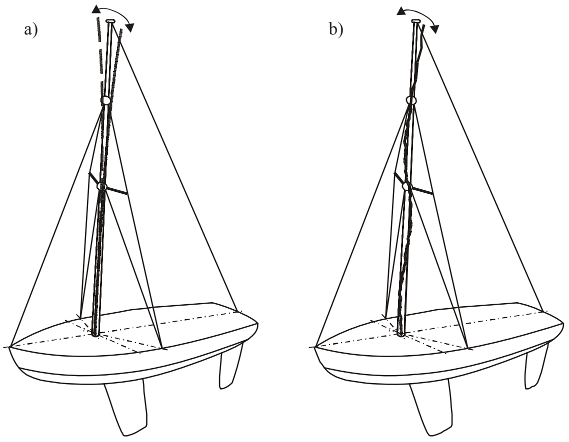

Fig. 1. Basic forms of transverse vibrations of masts: a) traditional, b) elastic (composite)

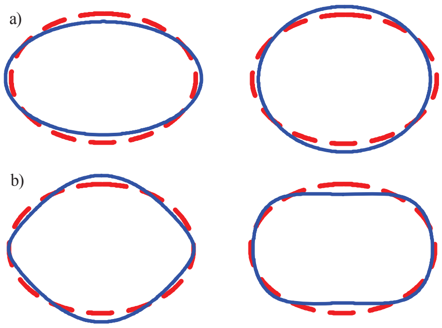

Fig. 2. Main forms of cross-sectional "shape" vibrations

Analysis of a composite mast vibrations caused by impulse forces, is much more complicated than the one of wooden or metal masts (Fig. 3).

Three zones (A, B, C) can be isolated in the vibration spectrum. The spectrum pattern – in the range of low frequencies (A) – corresponds to weakly non-linear vibrations of a beam of a non-symmetrical cross-section. In the range of higher frequencies (B), vibrations become strongly non-linear, while in the range of the highest frequencies (C) vibrations contain surface and cross-sectional vibrations. The dynamic response, in the first zone, is very sensitive e.g. to the location of modal points. The question arises: how to select the location of these points to have an aerodynamically acceptable vibration level without increasing the number of ropes?

The answer, on the basis of solving equations of beam transverse vibrations at the properly assumed boundary conditions (taking into account the rigging elasticity – in a rather complicated form), occurs to be very inaccurate even for the first two harmonics and completely unreasonable for the consecutive ones. Such differential model is unidentifiable. Similar situation concerns, for the time being, the FEM model [3].

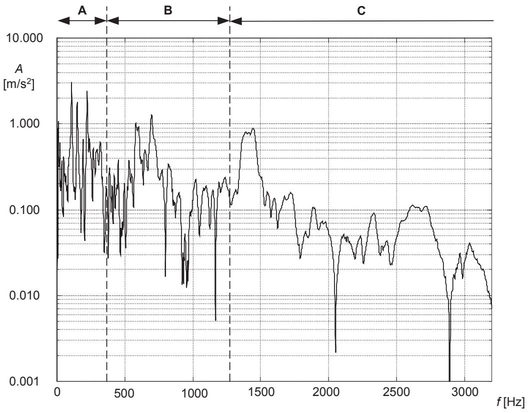

Fig. 3. Spectrum of vibration accelerations of a composite masts with marked zones: A – transverse vibrations, B – non-linear effects, C – cross-sectional shape vibrations and surface vibrations

Composite material properties are the reason for such situation. Equivalent Young's modulus changes non-linearly both in a displacement function in static tests and in a deformation rate function, and a character of those changes significantly differs for various designs (Fig. 4). Differences are already significant for the first harmonic. For the next two or three harmonics the errors slightly increase, while for the successive ones the results are completely senseless. Thus, the task requires – in its essential part - empirical investigations.

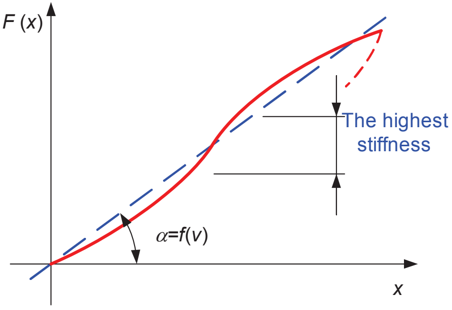

Fig. 4. Example of composite characteristics

3. APPLICATION OF A NORMAL COHERENCE FUNCTION

For the linear system the dependence change in the time and frequency domain is effective (Fig. 5):

$$\ddot{\xi}_i + \omega_o^2 = p_i(t) \rightarrow \xi_i = p_i(t) * h_i(t-\tau) \tag{1}$$

$$\Im \xi_i = P_i(\omega) \cdot H_i(\omega, i) \tag{2}$$

which corresponds to the coherence function equal 1.

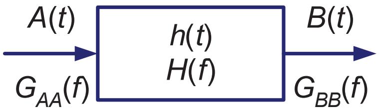

Fig. 5. Schematic presentation of a simple linear system

$$\gamma^2_{AB}(f) = \frac{|G_{AB}(f)|^2}{G_{AA}(f) \cdot G_{BB}(f)} \tag{3}$$

However, for the non-linear system, where the Principle of Superposition is not binding, one can discuss a disturbance as a "deviation" from the linear Equation [4], in a following way (Fig. 6):

$$\ddot{\xi}_i + \omega_o^2 = p_i(t) \rightarrow$$
$$\xi_i = p_i(t) * h_i(t-\tau) + \varphi(\xi_1, \ldots, \xi_i) \tag{4}$$

$$\Im \xi_i = P_i(\omega) \cdot H_i(\omega, i) + \Phi(\xi_1, \ldots, \xi_i) \tag{5}$$

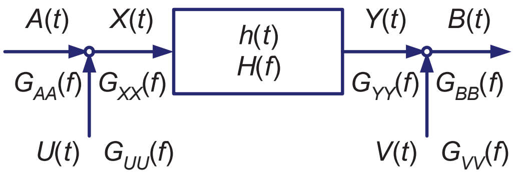

Fig. 6. Schematic presentation of a system with a disturbance

A non-linear disturbance of such a system can be interpreted as a simultaneous disturbance of input and output, which allows to extract the 'non-linearity' from the normal coherence function, according to the dependence (Fig. 7):

$$\gamma_{AB}{}^2(f) = \gamma_{XY}{}^2(f) \Big/ 1 + G_{UU}(f)/G_{AA}(f) + \ldots$$
$$\ldots + G_{VV}(f)/G_{BB}(f) + G_{UU}(f)/G_{AA} \cdot \ldots \tag{6}$$
$$\ldots \cdot G_{VV}(f)/(f)G_{BB}(f)$$

$$\gamma_{AB}{}^2(f) = \frac{\gamma_{XY}{}^2(f)}{1+\mathit{\Delta}(f)} = \frac{H_1(f)}{H_2(f)} \cdot \frac{1}{1+\mathit{\Delta}(f)} \tag{7}$$

$$\gamma_{AB}{}^2(f) = \frac{\gamma_{XY}{}^2(f)}{1+\mathit{\Delta}(f)} = \frac{H_1(f)}{H_2(f)} \cdot \frac{1}{1+\mathit{\Delta}(f)} \tag{9}$$
$$\Delta(f) \Rightarrow \varphi_i(f)$$

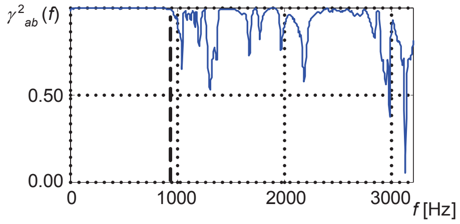

Fig. 7. Example of a normal coherence function for a system with non-linear disturbances

4. MEASUREMENTS WITH AN APPLICATION OF BRAGG'S GRATINGS

Composite materials are characterised by a particular property, which is the impossibility of determining the Young's modulus. Instead, an equivalent of the Young's modulus is used, which is changing non-linearly both in a displacement function in static tests and in a deformation rate function, and a character of those changes significantly differs for various structural solution. Due to a significant influence of deformation its accurate determination is required. This concerns especially dynamic tests of masts, in which a preliminary rigging tension is applied to obtain the required shape.

The most often strain gauges systems are used in a measuring technique of deformations. Apart from several advantages they have certain faults, which render difficult their application in dynamic measurements of yacht masts, especially in natural conditions. Now-a-days, together with the technological development, Bragg's gratings appeared (FBG – Fibre Bragg Grating) [5]. They are optical wave sensors, in which changing of a light wave length is applied e.g. for monitoring deformations (since there is a linear dependence: *deformation→light wave length change*).

Utilisation of Bragg's gratings requires the application of a spectrum analyser as well as a light source (laser one of a given wave length). The application of various wave lengths allows to use a few Bragg's gratings in series on one optical wave sensor. Main advantages of their application are as follows:

- change of Bragg's wave length is a linear function of the measured value – in a wide range,
- information on the measured value is coded in a form of the wave length change and therefore noises or power losses do not influence the sensor signal,
- due to a small diameter and low weight they can be placed in composite materials without disturbing their structure,
- they are electromagnetic field resistant,
- no current is flowing, so there is no sparkling and they are water influence resistant,
- there is a possibility of installing a few sensors on one optical wave guide (the measuring system only negligibly interferes with a composite structure),
- there are small energy losses, which means that the optical wave guide length does not influence the measurements.

5. CONCLUSIONS

Preliminary, comparative examinations with the application of strain gauges and Bragg's gratings were performed in the laboratory conditions. Simultaneously vibration accelerations were recorded in places of deformation measurements. The testing stand for measuring dynamic influences of composite masts is presented in Figure 8. It consists of a stiff foundation, stiff mast fixing and rigging allowing to introduce the given shape of the mast deflection.

Due to the application of the vibration exciter TIRA TV5500/LS the dynamic analysis of mast vibrations can be performed not only for impulse forcing but also for periodical forces (e.g. harmonic) or random ones.

The performed examinations indicate high usefulness of the fibre Bragg's gratings.

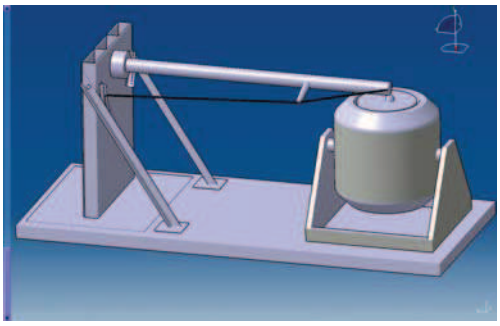

Fig. 8. Scheme of the testing stand

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Jacek DZIURDŹ, Ph. D. M. Eng. – graduate of the Faculty of Cars and Working Machines of the Warsaw University of Technology. Adiunct in the Institute of Basics of Machine Building of the Warsaw University of Technology. His research field: machine diagnostics, machine vibroacoustics and signal analysis. Author of more than 40 papers from the field of vibroacoustic diagnostics and digital analysis of signals. Member of the Polish Association of Technical Diagnostics, Secretary of the Vibroacoustics Section of the Acoustics Committee of the Polish Academy of Sciences.

Wojciech SKÓRSKI, Ph. D. M. Eng. – graduate of the Faculty of Mechanics, Power Engineering and Aviation of the Warsaw University of Technology. Adiunct in the Institute of Aircraft Engineering and Applied Mechanics. Designer and constructor of sailing yachts. Deals with building and testing of yachts as well as their equipment.