Vibration-based structural health monitoring of the aircraft large component

V Pavelko, S Kuznetsov, A Nevsy and M Marinbah
Institute of Aeronautics, Riga Technical University, 1A Lomonosova iela, Riga LV1003, Latvia
E-mail: Vitalijs.Pavelko@rtu.lv

Abstract. In the presented paper there are investigated the basic problems of the local system of SHM of large scale aircraft component. Vibration-based damage detection is accepted as a basic condition, and main attention focused to a low-cost solution that would be attractive for practice. The conditions of small damage detection in the full scale structural component at low-frequency excitation were defined in analytical study and modal FEA. In experimental study the dynamic test of the helicopter Mi-8 tail beam was performed at harmonic excitation with frequency close to first natural frequency of the beam. The index of correlation coefficient deviation (CCD) was used for extraction of the features due to embedded pseudo-damage. It is shown that the problem of vibration-based detection of a small damage in the large scale structure at low-frequency excitation can be solved successfully.

1. Introduction
Vibration-based damage detection is one of the most attractive for structural health monitoring (SHM). Because modal characteristics of a structure are directly related to physical properties of the structure, (mass, stiffness, and damping) then they can be used to detect, locate, and characterize damage in the structure [1]. There are large number of research and developments in mechanical, civil, and aerospace engineering dedicated to vibration-based damage detection. Some corresponding review-information can find in [2-9]. Methods that use changes of natural frequencies due to presence of damage usually require simple vibration measurements for estimation of position and growth of damage after calibration or accurate physics-based simulation. The mode shapes directly provide also spatial information of structural changes due to damage. Curvature mode shapes can be more sensitive and more effectively used to identify damage [10, 11].

Two basic techniques are used for practical realising of the vibration-based damage detection. Traditional is the experimental modal analysis (EMA) that allows more complete and accurate to identify damage. However, the EMA requires the measurement of both the input and the output of dynamically loaded structure. Other the operational modal analysis (OMA) uses output only, is cheaper and faster than EMA and can be easily applied to large structure [12].

In the presented paper there are investigated the principal problems of the local system of SHM of large scale aircraft component. Vibration-based damage detection is accepted as a basic condition, and main attention focused to a low-cost solution that would be attractive for practice.
2. Aims and motivation
The global aim of research is a problem of vibration-based method of NDT application for SHM based on some solution for a relatively small structural damage detection using operational low-frequency excitation (OMA approach).

It is known, the direct modal analysis is or low sensitive or difficult for practical application in operation. If the scale of damage is small in comparison with structure dimensions, then effect of damage is significant only for higher modes of structure. For example, there are number of analytical and experimental investigations of crack or additional small mass effect to dynamic properties of the cantilever beam [13-18] those confirm appreciable shift of separate higher natural frequencies only and change of corresponding mode shapes. Later ones show location of damage, but for the reliable indication of damage the branched net of sensors is needed.

Bet theoretically any response of linear dynamic system is a linear combination of all modes. The principal question: is effect of damage sufficient for its detection of the available vibration-based technique of NDT? Other question is associated with the fitness of this technique for implementation in the SHM system. Some acceptable solution can be find, if its application will be a priori restricted by some conditions. The main of them is restriction of dimensions of monitored zone of structure. By other words the SHM system should be local. Second condition accepted in this paper: the SHM system should be objectively oriented (the type of damage, its location, acceptable detectable size should be known). At those conditions the local vibration-based SHM system can be developed and has some perspective of practical application in operation.

More detailed description of investigation aim is followed.
There is a large full-scale component of some structure. In fixed zone of structure a structural damage is expected. A few sensors are embedded in this zone for vibration measurement at low frequency excitation. More precise, the excitation basic frequency is close to the first natural frequency of full structure and is much smaller than the first “local” natural frequency of a monitored zone. The investigation of this problem and development of some approach of extraction of damage features is detailed aim of presented paper.

3. Short description of the full scale structural component of aircraft
The helicopter Mi-8 tail beam structure was selected for experimental investigation (general view in figure 1). The beam has the form of the truncated cone with a length of 5485 mm, and the diameters of end cross-sections are 1000 and 550 mm respectively. The material of all main elements of the beam is the aluminium alloy D16AT (close to Al2024-T3). A skin thickness is in interval 0.5-0.8 mm. Stringers (total number 26 ones) of angular cross-section are connected to the skin by spot-welding. The 17 frames are riveted to the skin. There are number of non-regularities of structure of the beam due to technological and operational requirements (hatches, connection units, transmission supports, etc.) that are the potential sources of skin damaging in operation.

Figure 1. General view of the helicopter Mi-8 tail beam (a) and the test setup for dynamic loading (b), 1- the tail beam, 2- imitator of the tail rotor beam, 3 – the eccentric shaker.
4. Analytical estimate and modal FEA

The effect of damage to dynamic properties of a structure was estimated by general linear model of structure with embedded small 1D oscillator. Latter one is simulated the local mass/stiffness variation of structure parameters due to a damage. Finally, the dynamic response of linear system at harmonic excitation can be presented in equation (1).

\[ u(x, t) = \sum_{k=1}^{\infty} U_k(x) \theta_k(t) \]  (1)

where \( U_k(x) \) and \( \theta_k(t) \) are the modal vector and the normal function of the \( k^{th} \) mode of free oscillation. Note that the modal vector corresponds to intact structure.

At harmonic excitation with a circular frequency \( \omega \) the normal function of the \( k^{th} \) mode is:

\[ \theta_k(t) = A_k(\omega)e^{j\omega t} \]  (2)

\[ A_k(\omega) = \frac{\Phi_k}{M_k(1 - \bar{\omega}^2) + m(\xi_0)U_k(\xi_0)(\omega_{dk}^2 - \omega^2)} \]  (3)

where \( M_k \) and \( \Phi_k = \iint F_0(\xi)U_k(\xi)d\xi \) are the modal mass and modal force of the \( k^{th} \) mode. The modal frequency of damaged structure \( \omega_{dk}^2 \) is defined in equation (4).

\[ \omega_{dk}^2 = \omega_k^2 \left[ 1 + \frac{m(\xi_0)U_k(\xi_0)U_k(\xi_0)}{M_k(1 - \bar{\omega}^2)} \right]^{-1} \]  (4)

here \( u(\xi_0) \) is a vector-amplitude of oscillation of main structure in a base of oscillator. Excitation relative circular frequency \( \bar{\omega} \) is given in respect to the natural frequency of oscillator.

Equations 3 and 4 define the effect of damage to modal frequency and amplitude of harmonically forced vibration. From equation 4 it is seen that this effect can be appreciable only for mode with modal and excitation frequencies close to the natural frequency of oscillator and at the condition that the mass of equivalent oscillator is not very small in comparison with modal mass \( M_k \). The effect of damage is more complex and defined by variation of modal frequency and modal mass.

So the effect of small damage practically cannot be reliably detected at low-frequency excitation in conditions of formulated problem using only modal analysis of output signal. However, in practice, the input signal often contains high-frequency components (for example, white noise). In this case, high eigenfrequencies due to local design properties of structure can be detected in the spectral decomposition of the output signal. Obviously that a small-size defect most significantly affects the dynamic response of the structure in the damaged zone. For this purpose, an analysis of the local dynamic properties of the object of investigation was carried out. The tested tail beam has a thin-walled quasiperiodic structure. Its elementary structural unit is the skin fragment bounded by two adjacent stringers (in the circumferential direction) and two adjacent frames (in the longitudinal direction).

Below there is presented the results of a local modal analysis of small 0.5 mm thin-walled panel of the tail beam. The cylindrical panel with 450 mm of curvature radius simulates a portion between two frames (distance 372mm) and cover three stringers (figure 2, a). Total length of a curved edge of a panel is equal to 218 mm. The pin-type boundary condition is selected at all contour of a panel. As a result, the conditions of dynamic behaviour of middle stringer and close part of a skin were estimated as similar to the same part in assembled structure. The Autodesk Inventor was used for both geometrical simulation and modal FEA.

In figure 2 the CAD model of a panel, and its views with two types of pseudo-damage (PD) are shown. More details description of PD is given below.
Several results of modal FEA are presented in figure 3. First natural frequency is equal to 367.91 Hz for intact panel, 383.08 Hz for SPD, and 274.63 Hz for LPD.

So, a small damage of structure is able appreciably affect to local dynamic properties of some small part of structure. It is seen also that such damage effect to general dynamic properties of a structure is limited by the local changing of shape of the mode which natural frequency is closest to local natural frequency of damaged zone.

5. Experimental study

5.1. The objectives of test:
1) Measurement of the strain/stress state of some aircraft full-scale component at dynamic loading.
2) Experimental investigation of pseudo-damage effect to the strain/stress state of skin of the tail beam at nominally harmonic excitation.

5.2. Test setup
Test setup contents the test portal as a base for fixing of the tail beam, the imitator of the tail rotor beam, and the eccentric shaker with electromechanical drive (figure 1, b). In contrast to usual practice of vibration test, the strain gauge technique was used for the dynamic measurement. Two strain gauge rosettes were pasted in two zone of the outer surface of a skin. In the Figure 4, a the rosette in the zone 2 is shown.

The technology of pseudo damage was used for damage effect simulation. Pseudo damage is a non-destructive modification of a test object which affects local dynamics properties of a testing structure [19-21]. The small pseudo damage (SPD) was completed as row of eight 6×6×6mm steel blocks (total mass 12 g) and placed in the zone 1 (figure 4, b). Two steel blocks (total mass 26 g) were pasted in the zone 2 and qualified as large pseudo damage (LPD).

Dynamic strain was measured by the multichannel oscilloscope NI PXIe-4330, 16Ch, 24-Bit, 25 kS/s Bridge Input Module and PC with NI LabVIEW software. The sampling rate 5 kS/s and the length of a record in 5s were accepted as optimal for the data acquisition sufficient for the aim of experimental study. Cyclic excitation of vibration was limited by frequency band close to the first natural frequency of a beam (3.9 Hz).
5.3. Test results
The main results of test for excitation frequency 3.8 Hz is presented below. Using strain measurement data, the components of plain stress state $\sigma_x$, $\sigma_y$, $\tau_{xy}$ were defined in both zones. It is accepted that the axis $x$ coincident with longitudinal direction of a beam and the axis $y$ is perpendicular to first one.

![Image of test results](image)

**Figure 4.** A rosette of three strain gauges (a) and a strain gauge rosette with the small pseudo damage (SPD) in zone 2 (b).

![Image of stress components](image)

**Figure 5.** The components of stress state in the zone 1 as time functions (a) and spectrum of stress component $\sigma_x$ in the frequency band 0-400Hz in the zone 1 (b).

![Image of stress spectra](image)

**Figure 6.** Spectrum of stress component $\sigma_y$ (a) and stress component $\tau_{xy}$ in the frequency band 0-400Hz in the zone 1.
Typical stress/time functions are shown in the figure 5.a for stress state in the zone 1. Fast Fourier transform (FFT) was done for each of three stress components (figures 5b, 6) for intact and structure with a pseudo-damage. Similar results for zone 2 with LPD are presented in figures 10, 11, 12. Spectral transform allows to define directly the resonance frequencies 3.9, 20.6, 38.6, 65.0 Hz that was confirmed also by the direct measurement in process of dynamic test. Significant peaks of spectrum are also at frequencies 83.8, 121.2, 136.6 Hz. It can be seen that any shift of mentioned resonance frequencies is not observed at presence of PD. In the frequency band 150-275 Hz the amplitude of spectrum is distributed with relatively small fluctuation. Amplitude of spectrum sharply increases in the frequency band 275-400 Hz.

The spectrum of all components of stress for structure with PD is close to corresponding spectrum of the intact structure.

Interesting result is obtained for the spectrum of stress component σ_y (lateral direction): the amplitude of spectrum is large practically in the frequency band 275-400 Hz only (figure 7).

**Figure 7.** Spectrum of stress component σ_x (a) and stress component σ_y (b) in the frequency band 0-400Hz in the zone 2.

6. Discussion and feature extraction

As noted above, the tested beam has a quasiperiodic structure. Therefore, it can be assumed that there is an interaction of neighboring structural units and the existence of many eigenmodes of the beam vibration in a narrow frequency band. Indeed, an additional modal analysis of the more complex part of the beam that consists 39 structural units shows that there are at least fifteen independent eigenmodes in the frequency band 280-390 Hz. In the same limits, intensive increasing of response spectrum is observed in test (figures 5-7). This can be explained by the presence of a close spectrum of natural frequencies in the band 275-400 Hz.

At the same time, changes in the spectral power of response due to the appearance of damage can be seen. Moreover, the complexity of the dynamic response spectrum in the frequency band of interest causes difficulties of defect identification by the shift of the natural frequency and the change in the shape of the modes.

Therefore, variants of the integral estimation of the change in the response spectrum were considered. The most successful is the use of the correlation coefficient deviation (CCD) index that is widely used in different applications [22-25].

\[
CCD = 1 - CC
\]

where

\[
CC = \frac{\text{cov}(x, y)}{s_x s_y}
\]

\(\text{cov}(x, y)\) is the covariance between two sample random vectors \(x\) and \(y\) those are the spectrum of response of intact and damaged structures respectively in selected frequency band, and \(s_x, s_y\)
are the standard deviations of random vectors. It is seen that the \( CCD \) index is equal to zero, if there is not any damage effect, and cannot be more than 1. The larger value of the \( CCD \) index corresponds to higher effect of damage.

In figure 8 the comparison of \( CCD \) indices of damaged (with LPD and SPD) structures are shown for the spectrum of dynamic response at excitation nominal frequency 3.8 Hz. It is seen that the \( CCD \) index increment due to pseudo-damage is observed for all stress components. At the same time, the damage effect is greater for a larger pseudo-defect.

![Figure 8. Effect of pseudo-damage to CCD index.](image)

The important aspect of this index application is the requirements to input signal. A general assumption in the theory of OMA concerns the input which is not measured and consists of a Gaussian white noise with a flat spectrum in the frequency band of interest [12]. At the nominally harmonic excitation with frequency close to first resonance the intensities of output for intact and damaged structures may be different. Therefore, the processing of each record of the output signal must provide of its normalization before the operation of determining the index. The mean amplitude of output was used here as acceptable estimate of output intensity.

7. Conclusions

Vibration-based damage detection is accepted as a base of local SHM, and main attention focused to a low-cost solution that would be attractive for practice. It is shown that the possible solution can be obtained, if several requirements are satisfied.

First of all, the input of monitored structure is nominally harmonic or steady operational process with non-zeros spectral power in the frequency band of interest. The regime of excitation near resonance frequency is preferred for obtaining the output as much as possible. The monitored zone of structure close to the expected damage should be determined by a priori structural analysis or using test results. The first “local” eigenfrequency of monitored zone of structural component should be estimated also.

At the practical implementation of a local SHM system one or a few sensors should be placed in the monitored zone for output measuring. The baseline of dynamic response of intact structure at accepted regime of excitation defines the intact of monitored structure. The comparison of current measurement of output signal with the baseline gives the \( CCD \) index for estimation of structural health of structure.

Results of research show that the problem of vibration-based detection of a small damage in the large-scale structure at low-frequency excitation can be solved successfully.

References:
[1] Doebling S W, Farrar C R, and Prime M B 1998 Shock Vib Dig 30(2) 91
[2] Conte J P, He X, Moaveni B, Masri S F, Caffrey J P, Wahbeh M, Tashihgoo F, Whang D H, and Elgamal A 2008 Journal of Structural Engineering ASCE 134(6) 871
[3] Peeters B, Maeck J, and De Roeck G Smart materials and Structures 2001 10 518
[4] Schubel P J, Crossley R J, Boateng E K G, Hutchinson J R 2013 Renewable Energy 51 113
[5] He K, and Zhu W D 2014 ASME J. Vib Acoust 136(3) 034503
[6] Sohn H, Farrar C, Hunter N, and Worden K 2003 Los Alamos National Laboratory report LA-13976-MS
[7] Cardin E P, and Fanning P 2004 Structural Health Monitoring 3 355
[8] Farrar C R, Doebling S W, and Nix D A 2001 Phil Trans Roy Soc A Mathematical, Physical and Engineering Sciences 359(1778) 131
[9] Jun Lia, and Hong Hao 2016 Structural Monitoring and Maintenance 3(1) 33
[10] Pandey A K, Biswas M, and Samman M M 1991 J Sound Vib 145(2) 321
[11] Ratcliffe C P 2000 ASME J Vib Acoust 122(3) 324
[12] Reynders E 2012 Archives of Computational Methods in Engineering 19 51
[13] Pavelko V, and Shakhmansky G 1971 Trans of Riga Institute of Civil Aviation 191 18
[14] Pavelko I, and Pavelko V 1997 Proc Int Conf. (Pranesimus medziaga Transporto priemones – 97) Kaunas, Lithuania. Technology 237
[15] Ebrahimi A, Behzad M, and Meghdari A 2010 Int J Mech Sci 52 904
[16] Swapnil Dokhe, and Shailesh Pimpale 2015 Int J Res Aer Mech Eng 3(8) 24
[17] Liang RY, Hu J L, and Choy F 1992 J Eng Mech-ASCE 118 384
[18] Kasper D G, Swanson D C, and Reichard K M 2008 Journal of Sound and Vibration 312 1
[19] Pfeiffer H, Pitropakis I, and Wevers M. 2010 Proc 10th European Conference on Non-Destructive Testing Moscow www.ndt.net
[20] Prakash Rajendrana, and Sivakumar M Srinivasan 2015 Structural Engineering and Mechanics 54 (4) 711
[21] Pitropakis I, Pfeiffer H, and Wevers M. 2012 Sensors and Actuators A Physical 176 57
[22] Mays L W, and Tung Y K 1992 Engineering and Management McGraw-Hill, NY USA
[23] Naidu A S K, Bhalla S, and Soh C K 2002 Proc SPIE 4935 473
[24] Giurgiutiu V, Zagrai A, and Bao J J 2002 Int J Structural Health Monitoring 1 41
[25] Annamdas V G M, and Soh Ch K 2010 J Intel Mat Syst Struct 21 41