Operational Modal Analysis on a Modified Helicopter

E. Camargo[+], N-J. Jacobsen[*], D. Strafacci[+]

[+] Centro Técnico Aeroespacial,
Instituto de Aeronáutica e Espaço, Praça Eduardo Gomes, 50, 12.228-904
São José dos Campos, SP, Brazil

[*] Brüel & Kjær Sound & Vibration Measurement A/S
Skodsborgvej 307, DK-2850 Nærum, Denmark

ABSTRACT

Two mounts were added to a helicopter making it possible to carry different payloads. To validate the structural effects of these modifications, modal tests were performed on-ground on the helicopter in its standard configuration as well as in its modified configuration with the added payloads. In addition, an in-flight test was performed to verify the impact on the existing flight envelope. For all tests, Operational Modal Analysis was used. The obtained results allowed for updating the flight procedures and operating profiles for the helicopter and provided added flexibility with respect to the best possible helicopter configuration to obtain the mission objectives, while maintaining optimum safety for the flight crew.

1 Introduction

During flights, a helicopter’s tail structure undergoes significantly dynamic loads from aerodynamic flow and vibrations induced by the engine and rotors. Consequently, when modifications are made to a helicopter, the potential change in structural behavior of the tail section can be critical.

This paper presents different Operational Modal Analysis tests that were performed to study the change in the modal parameters on a helicopter after attaching a new payload system to it. The tests are essential to validate and refine the design of payload systems and provide information about internal stresses at critical locations. This information is required to avoid both helicopter tail damage thereby reducing the maintenance time between flights and to impose potential limitations to the flight paths.

In Chapter 2, the configurations of the helicopter are described together with the used test setups and instrumentation. In Chapter 3, the various Operational Modal Analysis tests and their assumptions are explained and the results are presented and discussed in Chapter 4. The conclusion is drawn in Chapter 5.

2 Configurations, Test Setups and Instrumentation

2.1 Configurations

Two different configurations were used to perform the measurements and analyses:

- Standard configuration of helicopter
- Modified configuration with payloads attached

The payloads were located on both sides of the helicopter close to the centre of gravity and consisted each of a rectangular plate. The configurations with accelerometer positions are shown in Fig. 1.

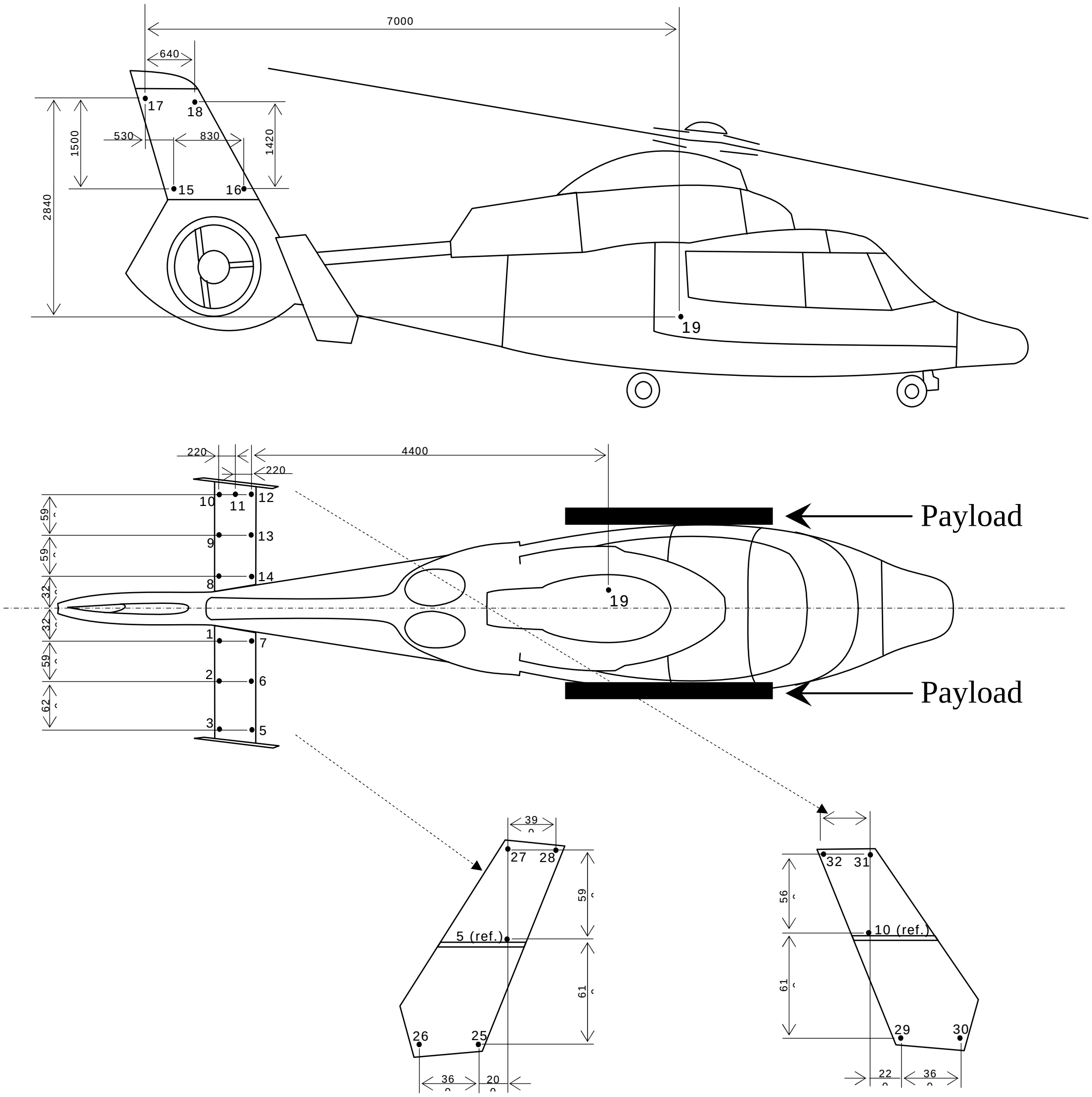

Fig. 1 Configurations and accelerometer positions

The number, positions and directions (DOFs) of the accelerometers were selected from simulation studies while at the same time keeping the number of DOFs down to reduce the instrumentation. The chosen DOFs were sufficient to obtain good mode shape estimates in a single measurement, thereby avoiding the need for using roving accelerometers. This gives the best possible data consistency and significantly reduces expensive test time.

For both the standard and modified helicopter configuration, the measurements were done using 26 accelerometers mounted on the tail section of the structure - 16 uniaxial accelerometers measuring in the global z-direction, 6 triaxial accelerometers measuring in the global y- and z-directions and 4 triaxial accelerometers measuring in all three global directions. For the modified helicopter configuration 5 additional triaxial accelerometers were added of which 4 were measuring in global y- and z-directions and one in all three global directions.

In Fig. 2, a model of the tail structure of the helicopter is shown, that is, from point 19 and backwards. A model of the payload is shown as well. Note that point 11 was not replicated on the opposite side as just one point was enough to predict the vibration level in the junction of the two structures. Also, the number of measurement DOFs could be reduced for the payloads.

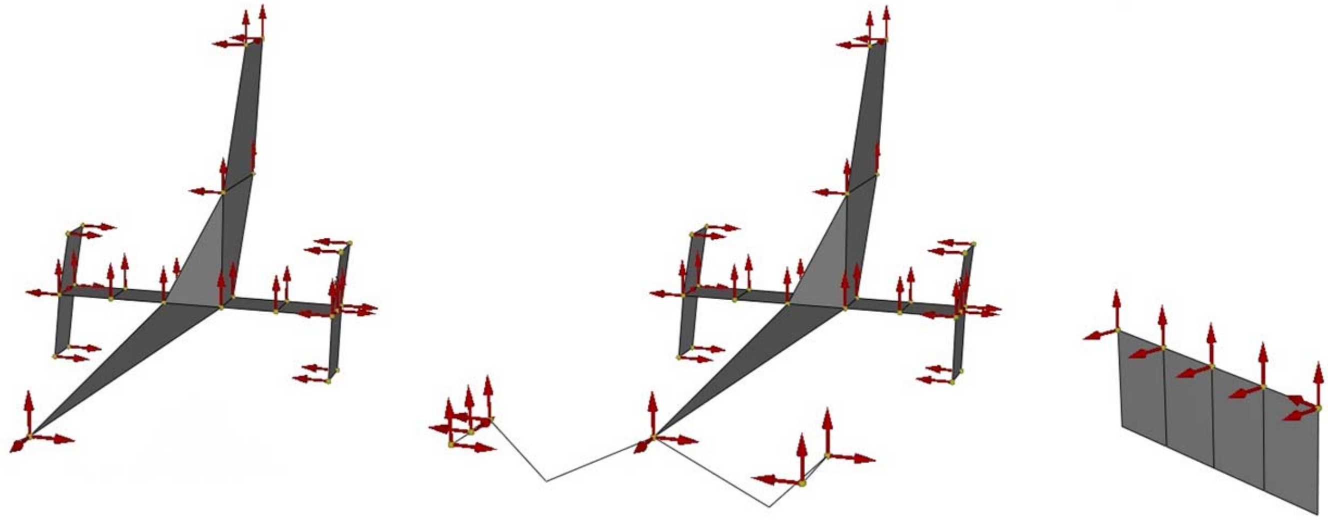

Fig. 2 Models used for the tests
Standard Helicopter (left), Modified Helicopter (middle), Payload (right)

2.2 Test Setups

Four different tests were performed:

- An *on-ground test* of the helicopter in its *standard* configuration using single shaker excitation
- An *in-flight test* of the helicopter in its *standard* configuration using internal and ambient excitation
- An *in-flight test* of the helicopter in its *modified* configuration using internal and ambient excitation
- An *on-ground test* of the payload system using hammer impact excitation

From the first two tests, the change in structural modes from ground to in-flight testing of the same standard helicopter configuration could be observed before making an in-flight test of the modified helicopter configuration. The test on the payload system was performed to predict and validate its structural effects on the modified helicopter. Examples of test setups are shown in Fig. 3.

2.3 Instrumentation

For all tests, data acquisition and analysis were performed using a Brüel & Kjær PULSE™ analyzer system consisting of three 17 channel Type 3560-C front-ends connected to a Dell Latitude D610 PC running PULSE™ software. Data acquisition and validation were performed using PULSE Modal Test Consultant™ Type 7753 software and modal parameter extraction using PULSE Operational Modal Analysis Type 7760 software.

The responses were measured using 15 Brüel & Kjær Miniature Triaxial Acclerometers Type 4520 and 16 Brüel & Kjær Uniaxial Accelerometers Type 4514 both of the piezoelectric type. For the shaker test, an LDS V455 permanent magnetic shaker with power amplifier PA 1000 was used. The impact testing was performed using a Brüel & Kjær One-pound Head Modal Sledge Hammer Type 8207.

Fig. 3 Examples of test setups
Shaker excitation (left), accelerometer mounting (top right) and front-ends (bottom right)

3 Operational Modal Analysis Tests

For all tests, Operational Modal Analysis was used to analyze the acquired time data. Operational Modal Analysis is based on stochastic processes and an underlying assumption for the identification techniques is that the excitation is from broadband random forces distributed over the structure (random in time and space) as described in [1]. Consequently, the excitation should ideally come from multiple broadband sources randomly distributed over the test object. This assumption is clearly fulfilled for the in-flight tests where the ambient excitation from the aerodynamic flow and the vibrations induced by the engine and the rotors by nature is broadband and random in time and space. In addition, harmonic components (deterministic signals) are present due to the rotational parts from the engine and rotors. There are techniques in the PULSE Operational Modal Analysis software that automatically identify and eliminate the influence of harmonic components so that they do not affect the obtained results. For more information on identification and elimination of harmonic components in Operational Modal Analysis see [2].

For the shaker test and the hammer impact test, the assumption is violated as regards the random excitation points as, in both cases, only a single excitation point was used. It was, however, considered acceptable to violate the assumption as previous classical modal analysis tests of the standard helicopter configuration showed identical results for the critical modes of interest. For the payload system itself the model was fairly simple and there was no notable limitation in selecting only a single excitation point.

Another important parameter in Operational Modal Analysis is the length of the time recording as explained in [2]. The required time recording length depends on various factors such as the spectral shape and duration of the excitation signal, presence of harmonic components, the complexity of the test object and the quality of the data acquisition equipment. However, as a rough rule of thumb, the time histories should be at least 500 times longer than the period of the lowest mode of interest. For the tests performed, the lowest modes of interest were above 30 Hz requiring a time recording length of at least 17 s which was fulfilled in all tests.

Using only Operational Modal Analysis for all tests simplified the complete test procedure and was, as such, an important objective to reduce expensive test time.

3.1 Analysis Parameters

All measurements were done in a 400 Hz frequency range using at least 60 s of time data. The Operational Modal Analyses were performed using the Enhanced Frequency Domain Decomposition (EFDD) peak-picking technique. A frequency resolution of 1 Hz was used in the underlying spectral estimation by using 512 frequency lines. The modal parameter estimation was performed using a MAC Rejection Level of 0.9 and the maximum and minimum correlation limits were set to 0.95 and 0.50, respectively.

An example of the EFDD technique is shown in Fig. 4 for the modified helicopter configuration during flight. For more information on the frequency domain decomposition techniques for Operational Modal Analysis, see [2] and [3].

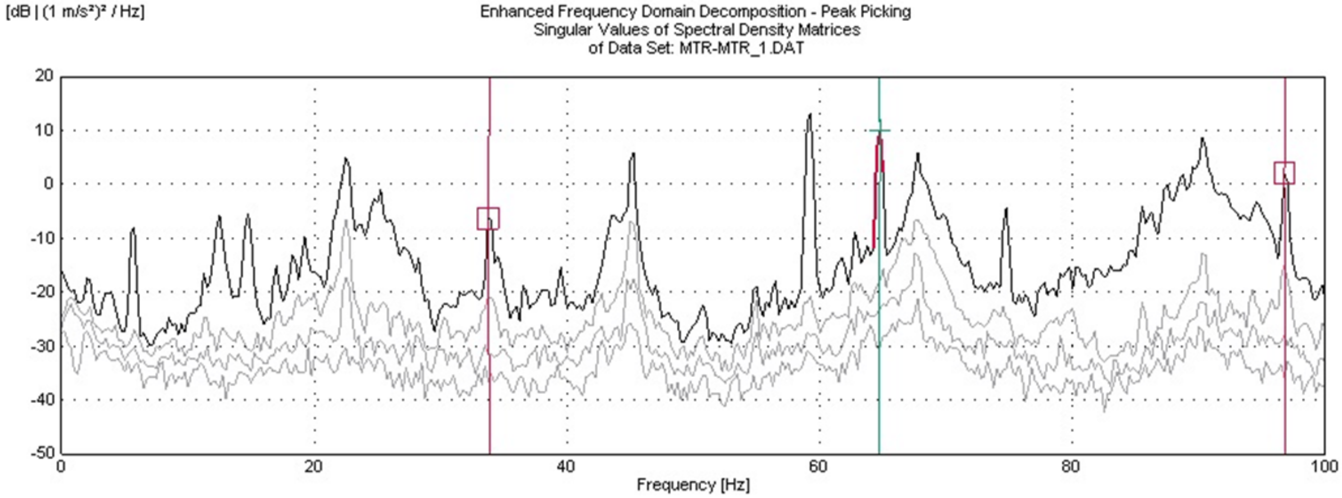

Fig. 4 EFDD used on data from the modified helicopter configuration during flight
The three main critical modes (33.9 Hz, 64.7 Hz, 96.9 Hz) are picked

4 Results

In this chapter the main results from the four different tests are presented and discussed.

4.1 On-ground Test Results of the Standard Helicopter Configuration

Two different tests were performed using single shaker excitation - one using random noise and one using swept sine as excitation signal. Both tests covered the frequency range from 10 Hz to 500 Hz. The swept sine test was, in general, found to give better stability in the estimation of the modal parameter and the results are summarized in Table 1.

Mode #	Frequency [Hz]	Damping Ratio [%]	Description
1	13	1.77	Rigid Body Pitch Mode
2	15	1.63	Rigid Body Roll Mode
3	28	1.82	1st Bending Mode of the Vertical Stabilizers (in-phase)
4	*36.0*	*2.24*	*1st Bending Mode of the Vertical Stabilizers (out-of-phase)*
5	57	1.63	1st Torsional Mode of the Vertical Stabilizers (out-of-phase)
6	*68.9*	*0.97*	*1st Torsional Mode of the Vertical Stabilizers (in-phase)*
7	90	0.79	1st Bending Mode of the Horizontal Stabilizer
8	*96.9*	*0.68*	*2ndBending Mode of the Horizontal Stabilizer*
9	106	0.58	1st Bending Mode of the Tail Fin
10	128	1.26	3rd Bending Mode of the Horizontal Stabilizer combined with Torsion of the Vertical Stabilizers (in-phase)
11	190	0.67	3rd Bending Mode of the Horizontal Stabilizer

Table 1 Selected modes up to 200 Hz of the standard helicopter configuration from shaker testing using swept sine excitation
The three main critical modes of interest are shown in *italics* and with increased accuracy

Using the results of this test and comparing it with the results of the standard helicopter during flight made it possible to find the critical modes, that is, modes where the natural frequency is significantly shifted and at the same time modes that significantly influence the structural and aerodynamic behavior of the helicopter. High vibration level at these frequencies can reduce the time between maintenance of the helicopter and are, therefore, important to know. The three most critical modes were found at 36.0 Hz, 68.9 Hz and 96.9 Hz. Fig. 5 shows the mode shapes at these critical natural frequencies.

Fig. 5 Mode shapes for the three most critical natural frequencies
Left to right: (36.0 Hz; 2.24%), (68.9 Hz; 0.97%) and (96.9 Hz; 0.68%)

4.2 In-flight Test Results of the Standard Helicopter Configuration

Measurements were done using four different flight path configurations.

- Hovering at 330 ft altitude (no influence from aerodynamic flow)
- Ascendant flights up to max. 8000 ft with increasing speed until reaching the speed limit of the helicopter
- Descendent flights
- Cruising at 3000 ft at different speeds including performing different pitch, roll and yaw maneuvers

The flight time for each path was 30 minutes with 60 s of data acquisition every 5 minutes.

The mode shapes at the critical natural frequencies are shown in Fig. 6.

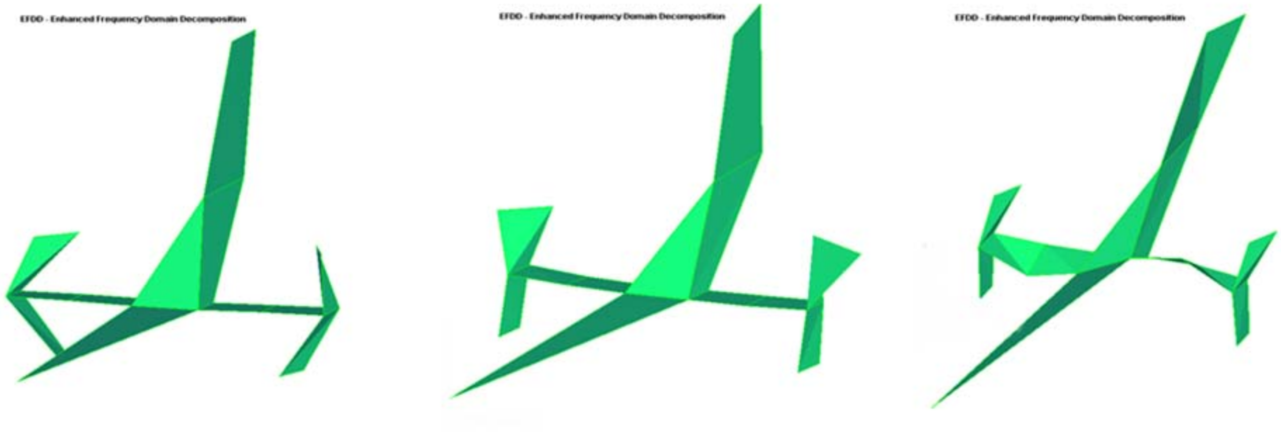

Fig. 6 Mode shapes for the three most critical natural frequencies
Left to right: (34.0 Hz; 2.01%), (65.2 Hz; 0.95%) and (97.5 Hz; 0.61%)

Comparing the results to the measurements made on-ground, the same mode shapes were observed but with a general downward shift in the natural frequencies as expected due to the added mass (flight crew, instrumentation) of the helicopter and the aerodynamic effects imposed on the tail structure.

It was observed that an increase in speed did not change the mode shapes, but caused increased vibration levels. Maneuvers were performed during cruising and apart from increased vibration levels some shifts in natural frequencies - especially at the helicopter's speed limit - were observed that are believed to be caused by the interference of the aerodynamic flow with the structure.

These observations were important to predict the structural behavior and thereby be able to increase the time between maintenance.

4.3 In-flight Test Results of the Modified Helicopter Configuration

The mode shapes at the critical natural frequencies are shown in Fig. 7.

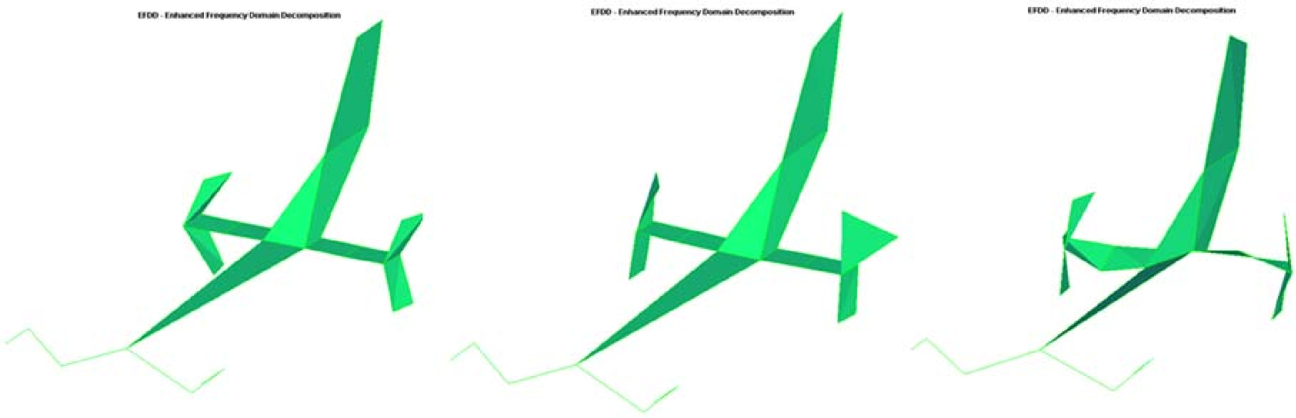

Fig. 7 Mode shapes for the three most critical natural frequencies
Left to right: (33.9 Hz; 0.43%), (64.7 Hz; 0.21%) and (96.9 Hz; 0.15%)

With payloads attached to the helicopter, an increase in the vibration levels was observed, but no significant reduction in the natural frequencies despite the added mass. Also more significant changes to the natural frequencies could have been expected due to interference of the aerodynamic flow through the stabilizers as the payloads were attached just on the same line as the horizontal stabilizers. This is, however, considered to be a likely explanation for the significant decrease in the observed damping ratios, but more studies need to be conducted to completely understand this phenomenon.

As shown in next section, the natural frequencies of the payloads were not coinciding with the beat frequencies of the helicopter's rotor and they were different to the natural frequencies of the helicopter structure. This leads us to conclude that the payloads can be attached to the helicopter without critically reducing the flight performance. Attention should, however, be paid when maneuvers are done close to the helicopter's speed limit if payloads are attached.

4.4 Test Results of the Payload

The analysis of the payload system was done using hammer impact excitation. The purpose was to understand how the payload system influences the aerodynamic flow along the tail section and to see if there were some coupling effects between the payload modes and the modes of the tail section. The modes found are shown in Table 2 and it can be seen that only the first mode of the payload is close to a critical mode of the helicopter's tail section. During flight no interferences were observed.

Mode #	Frequency [Hz]	Damping Ratio [%]	Description
1	29	1.77	1st Bending Mode
2	77	2.80	Torsional Asymmetric Mode
3	120	0.42	Combined Asymmetric Torsional with Bending Mode
4	199	1.13	Torsional Symmetric Mode

Table 2 Modes of the payload system from hammer impact testing

5 Conclusion

Operational Modal Analysis on a helicopter has been performed during flight with the helicopter in its standard configuration and in a modified configuration with payloads attached. The standard configuration of the helicopter was also tested on-ground. The results showed expected downward shifts in the natural frequencies during flight both for the standard and modified configuration. This was especially the case when the dynamics loads were increased with maneuvers at helicopter’s speed limit. The observed natural frequencies were presented and discussed. Lower damping ratios were found during flight and a large reduction was seen when the payloads were attached. This is expected to be caused by interference of the aerodynamic flow through the stabilizers but more studies have to be conducted. The critical mode shapes of the tail structure during flight were found to be identical to those found at the on-ground test.

The maximum vibration levels were observed during flight with payloads attached due to the forces induced by aerodynamic air flows. The vibration levels measured were, however, found to be within the limits established.

Maintenance time is not expected to increase as the attached payloads did not result in any observable reduction of the helicopter’s flight performance. Finally, it was found that by applying Operational Modal Analysis during flight the time used for testing can be reduced.

References

[1] Herlufsen, H; Andersen, P; Gade, S; Møller, N
Identification Techniques for Operational Modal Analysis – An Overview and Practical Experiences
1st IOMAC Conference, 2005

[2] Jacobsen, N.J.; Andersen, P
Operational Modal Analysis on Structures with Rotating Parts
23rd ISMA Conference, 2008

[3] Gade, S; Møller, N; Herlufsen, H; Konstantin-Hansen, H
Frequency Domain Techniques for Operational Modal Analysis
1st IOMAC Conference, 2005