# EXPERIMENTAL IDENTIFICATION OF THE FLEXIBILITY INFLUENCE MATRIX OF THE AIRCRAFT ENGINE MOUNTED ON PYLON UNDER THE WING

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**Abstract:** In this paper there is a description of the approach of the experimental definition of Elastic influence coefficients' matrix (ECM) using a number of linear displacements sensors and automated system of load application. Using the definition of the ECM of the engine mounted on wing of the dynamically-scaled model of the passenger aircraft as an example, the key characteristics of its realization are shown, which allow to minimize the main methodological inaccuracies.

## 1 INTRODUCTION

The one of the most common and dangerous flutter forms of the airplane with the engines mounted on pylon is so called wing-engine flutter form. The experimental research of this phenomenon starts on the early stages of aircraft design. With an appearance of the first full sized aggregates the experiments are carried out to update computation models. Expensive experimental research of the full scale object is usually preceded by test bed study of the separate aggregates and by the experimental work on aeroelastic models [1]. The demand for experimental research is mostly due to the difficulty to obtain the reliable analytical evaluation of actual elastic properties of the engine mount, which are often nonlinear.

In the experimental research of the aeroelastic properties of the airplane the engine mount is usually modeled by the spring with six degrees of freedom. Elastic influence coefficients' matrix (ECM), representing elastic properties of the spring, is obtained through the stiffness tests. To minimize the main methodological inaccuracies several key characteristics were implemented. These are such as optimized layout of sensors' of linear displacements, algorithms of ECM coefficients calculation.

Elastic influence matrix coefficients obtained as a result of the stiffness test could be used for the engine mounted under the wing computation models' verification for detailed research of such aeroelastic phenomena as wing-engine flutter.

## 2 TEST OBJECT

Stiffness tests are performed on engine mounted on the pylon under the wing. From the aeroelasticity viewpoint, this engine can be considered as non-deformable solid body with set mass-inertial characteristics. Engine has 6 degrees of freedom of movement and characteristics of its mounting could be obtained by measuring linear and angular displacements along all three axes, which are produced by the application of forces and momentums along all axes. To make a correct computation model of this object it is vital to apply loads correctly and measure displacements with good precision.

Carrying on the stiffness tests on such objects has some specifics. Multiple sensors have to be placed in limited space; it is desirable to eliminate the displacements of aircraft as whole solid object as well as deformations of the structure element on which the aggregate is mounted. This is a complicated and important problem as the elasticity of these elements may cause some serious inaccuracies in the experimental results. The stiffness along certain axis may vary considerably and non-linearly, depending on magnitude and on the sign of force applied along this axis as well as along the other ones. There also may occur hysteresis effects. To eliminate local deformations as well as displacement of the aircraft as a solid whole the sensors are mounted on solid support, which is rigidly mounted on the element to which the tested aggregate is attached. The placement of additional sensors can be required to make sure that the support is stationary in relation to the zone of its mounting. This approach allows to reach higher precision by using the sensors with lower measuring ranges and to reduce the amount of sensors required for measurements.

The test aggregate is assumed solid and non-deformable. Under such an assumption, six laser sensors are enough to determine the displacements of the object. Usage of additional sensors allows diminishing errors. Elastic model of the engine on the pylon and six sensors setup is shown on Figure 1.

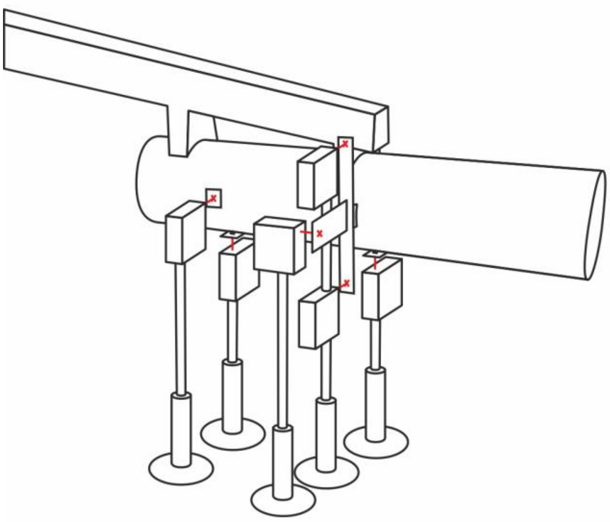

Figure 1: Stiffness test of the elastic model of the engine on pylon

In this case, the engine is mounted on a rigid wall, so no additional sensors are required and regular sensor stands can be used.

## 3 EXPERIMENTAL EQUIPMENT

As it can be seen on Figure 1, test object could have a complex shape and this require the usage of custom targets for laser sensors. Rapid prototyping systems (3D printing) is used to manufacture these custom targets, as the creating of the targets for each specific test object this way is much faster than traditional methods.

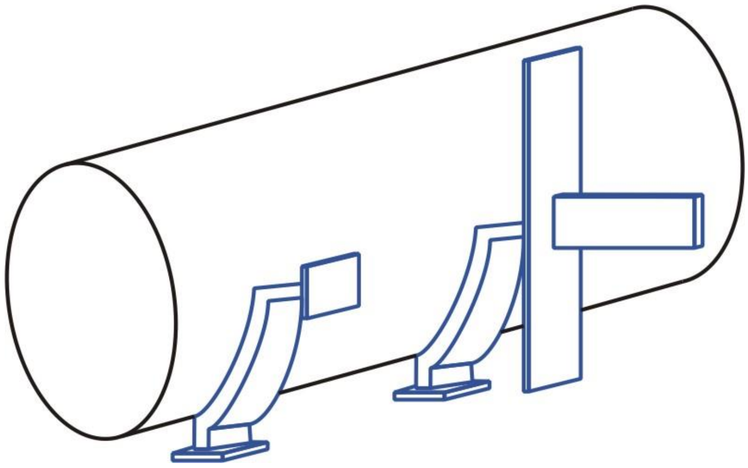

Figure 2: Targets for six sensors setup

Targets' placement for six sensors case is shown on Figure 2. This sensor layout has proven to yield accurate results for the displacements in the direction the load is applied, i.e. for diagonal elements of ECM. The placement of the sensors, their ranges, ranges and loading equipment greatly affect the precision of the results. Thus, it is very important to control these conditions. The quality of sensor targets and measurements' errors directly affect the quality of the results.

For more accurate measurements of non-diagonal elements of ECM it is advised to set up at least three sensors per target plane. Three sensors allow to calculate the displacement of one plane independently using the exact mathematical formula without the need of the data about displacements of two other planes. Addition of extra sensors per plane above three needed further increases the accuracy. Example of target placement for one of the three planes is shown on Figure 3.

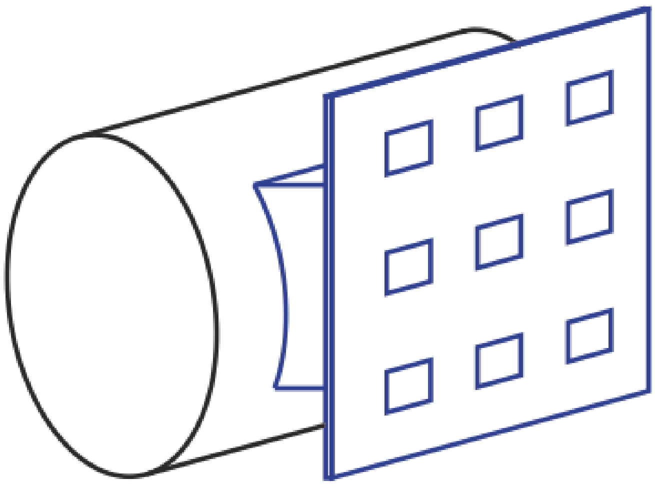

Figure 3: Example of targets' placement for multiple sensors per plane

The loading of the test object is accomplished by stepwise application of concentrated forces or pairs of forces. During application of each step of load the displacements in the fixed points are measured. Loads are usually applied by hydraulic cylinders, electric actuators and by using systems of blocks and hanged masses as shown on Figure 4. Hydraulic cylinders or electric actuators are incorporated into chains with the force sensors (usually a tensodynamometers) and auxiliary elements to provide required length of the chain. One end of the chain is attached through a hinge attachment unit to the test object and another end (also hinge connection) to the reinforced floor, wall or ceiling. Dynamometers are connected to the measuring system and are used for monitoring the value of forces applied.

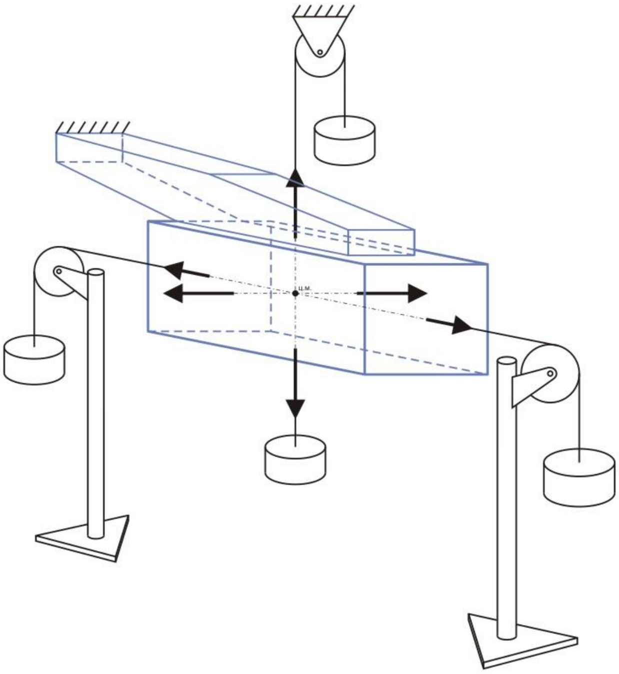

Figure 4: Application of forces using hanged masses

The best results are achieved by usage of automated system of load application. In this system electric actuators are used and data from force sensors and laser sensors is collected synchronously. The load could be applied fully automatically as well as directly controlled by the operator. Loads could be applied simultaneously in different directions and points, each point can have its own load profile. The system drastically shortens load cycle time and allows to apply the loads safely due to automated safeguards as well as operator controlled kill-switch. Electric actuators apply loads more steadily than hydraulic systems and does not require blocks. The system also increases the accuracy of the results by minimizing the human error factor, usage of electric actuators and good synchronization in data acquisition.

## 4 CALCULATION OF ELASTIC INFLUENCE COEFFICIENTS

The choice of elastic coefficients calculations' approach depends on number of the sensors used and the arrangement of those around the test object. The minimal amount of sensors required for the determination of full ECM is six, if the condition for certain sensors' configuration is met.

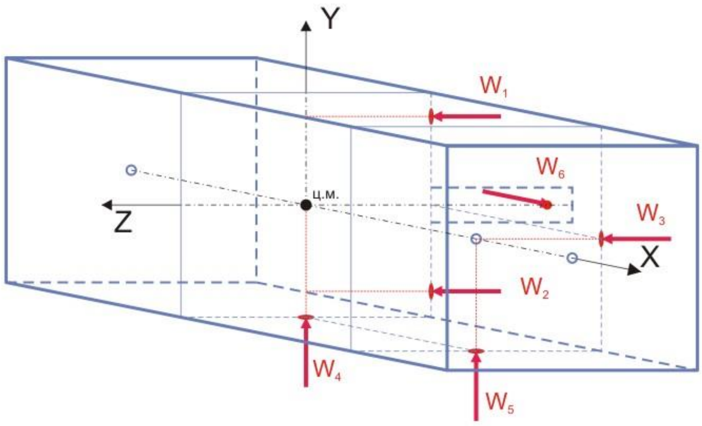


Figure 5: Sensor arrangement for six sensors case

Sensor arrangements for a six sensors setup is shown on Figure 5. For the ease of calculations, targets for all sensors, measuring the displacements in each direction, lie on one plane, perpendicular to the direction of measurement. The displacement of the center of the mass of the engine could be obtained from the displacements of these three planes. In addition, most sensors in this case lie in In addition, most sensors in this case lie in Oxz, Oxy, Oyz -planes of the coordinate system. The center of the coordinate system is a position of the center of mass of the engine before the application of loads. For six sensors setup the displacements there is an exact dependency between sensor readings $w_i$, where i is a sensor index, and the displacements of the center of mass:

$$w_1 = -b_1 \phi_x - \phi_y \Delta x + \phi_x \Delta y - \Delta z,$$

$$w_2 = b_1 \phi_x - \phi_y \Delta x + \phi_x \Delta y - \Delta z,$$

$$w_3 = a_3 \phi_y - \phi_y \Delta x + \phi_x \Delta y - \Delta z,$$

$$w_4 = -\phi_z \Delta x + \Delta y + \phi_x \Delta z,$$

$$w_5 = a_5 \phi_z - \phi_z \Delta x + \Delta y + \phi_x \Delta z,$$

$$w_6 = c_6 \phi_y + \Delta x + \phi_z \Delta y - \phi_y \Delta z, \quad (1)$$

- where $a_i$, $b_i$, $c_i$ are X, Y and Z-coordinates of a respective sensors; $\Delta x$, $\Delta y$, $\Delta z$ – are linear displacements of the center of mass; $\phi_x$, $\phi_y$, $\phi_z$ –angular displacements of the center of mass.

The angular displacements obtained from the set of the equations (1) is as follows:

$$\phi_x = (w_1 - w_2)/(2\, b_1),$$

$$\phi_y = (w_1 + w_2 - 2\, w_3)/(2\, a_3),$$

$$\phi_z = (-w_4 + w_5)/a_5, \quad (2)$$

- where $b_1$ and $–b_1$ are Y-coordinates of first two sensors, $a_3$ and $a_5$ are X-coordinates of the third and fifth sensor, respectively. The dependencies for linear displacements are obtained likewise, but the formulas are too long to be listed here. Each elastic influence coefficient is a coefficient in the linear dependency between displacement and load. The dependency between the linear displacement and the force applied is shown on Figure 6.

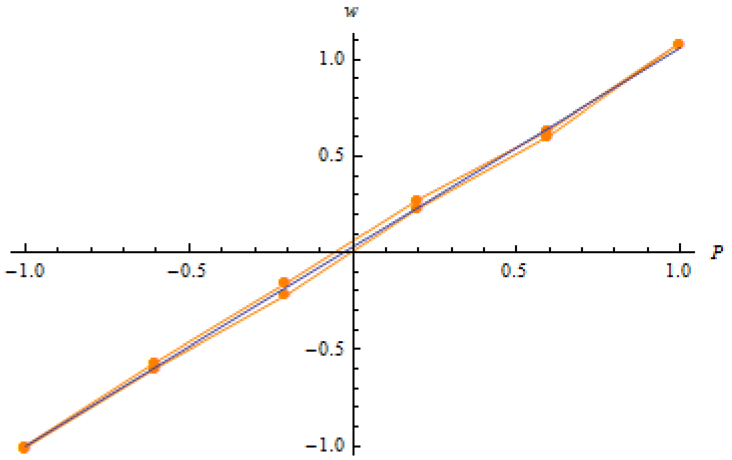

Figure 6: Dependency between the displacement and load

It should be noted, there is a slight are hysteresis effect and some non-linearity. Sometimes these effects are much more prominent and elastic coefficients actually depend heavily on the load range.

Multiple (more than 3) sensors per plane allow to achieve much higher accuracy with the same sensors. In this case the displacement of the center of mass is calculated from the displacements of target planes.

If the initial position of the target plane is that of the z=0 plane, then the readings $w_i$ of the sensor with index i could be represented as follows:

$$w_i = a\, x_i + b\, y_i + c \tag{3}$$

where $x_i$ and $y_i$ are coordinates of the respective sensor. To find coefficients a, b and c that determine the new position of the target plane the least square method is used. The values of a, b, c are found by minimizing the scalar product $\Delta W.\ \Delta W$, where:

$$\Delta W = (\Delta w_1, \ldots, \Delta w_i, \ldots, \Delta w_n),$$

$$\Delta w_i = w_i - (a\, x_i + b\, y_i + c) \tag{4}$$

Assuming the center mass is fixed in respect to target planes, its new position is easily calculated. The elastic coefficients are then calculated in the same way as for six sensors case.

## 5 NON-LINEAR EFFECTS

Some aircraft structure especially the ones with complex attachments, which is especially true for engines on pylon, often have substantially non-linear elastic properties, like those shown on Figure 7.

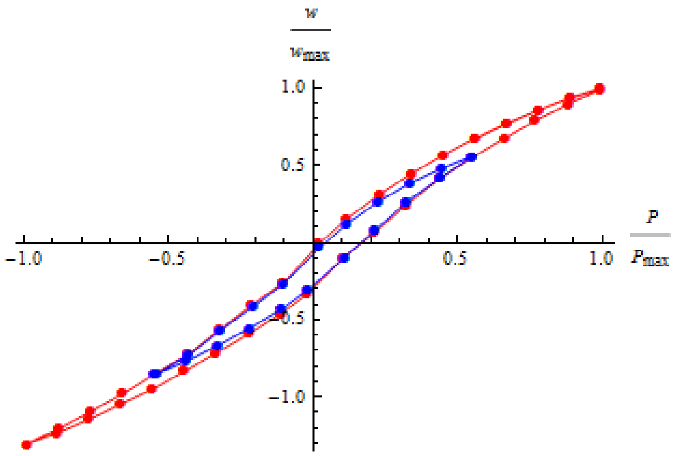

Figure 7: Hysteresis effect and severe non-linearity

As it can be seen, there is hysteresis effect and, in addition to that, the flexibility changes drastically with the load range (two cycles of load application with different ranges are shown). Multiple load applications with small steps as well as readings from several sensors proved that this not an experimental error, but a real tendency. Having a constant load like added weight in several cases proved to have an effect on elastic properties even if the load is applied along another axis. For this reasons we need to measure elastic properties of the object in question with good accuracy and the conditions of the experiment should match that of aircraft service conditions. In some cases the weight, thrust e.t.c. affect elastic characteristics and should be reproduced in tests.

## 6 CONCLUSION

Considered experimental approaches of the definition of elastic influence coefficients' matrix for different linear displacement sensors' layouts allow to reduce testing time and increase the quality of the results of stiffness tests of aircraft structures. Shown key characteristics of the process of experimental definition of the elastic properties of the engine on pylon using different systems of load application and special targets for optic sensors increase the precision of the measurements. Described algorithms of ECM coefficients calculation based on displacements and loads sensors' readings make it possible to conduct the calculations of the elastic influence coefficients in a short time for different layouts and quantities of sensors.

## 7 REFERENCES

Advanced Aeroservoelastic Testing and Data Analysis. – *AGARD-CP-566*, 1995

## 8 COPYRIGHT STATEMENT