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# A NOVEL METHOD FOR MOMENTS OF INERTIA TUNING FOR FREE-FLYING DYNAMICALLY SIMILAR MODELS VIA SIMULATED ANNEALING

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## ABSTRACT

In this study, a method was developed for tuning moments of inertia for a free-flying dynamically similar/scaled model of an aircraft. For this method, the simulated annealing optimization algorithm was used to obtain similar mass-inertial properties of the model and the full-scale aircraft utilizing ballast weights. For a scaled model of a Su-27 fighter, the ballast arrangement were designed and weights were determined to achieve the required center of gravity position and the moments of inertia based on the similitude requirements. A computer code was developed, and the task of tuning inertia properties was performed. The results showed that the proposed optimization approach was successfully used to determine a feasible ballast weight and position. Moreover, the ballast weight reduced from 8.66 kg to 4.86 kg using the proposed technique, and the inertia characteristics' non-similarity was minimized.

*Keywords:* Dynamically similar/scaled model; Moments of inertia; Optimization; Simulated annealing; Tuning

## 1. INTRODUCTION

A free-flying dynamically similar/scaled model (FDSM) of an aircraft is one of the most effective techniques used in aeronautical research, though there are challenges involved in its design and development (Chambers, 2009). Descriptions of the application and characteristics of FDSM are provided, followed by a discussion regarding the dynamic similarity and its requirements. Finally, the reasons that this research is necessary are discussed.

Aircraft design and development processes are used in different ways for aircraft behavior predictions, such as theoretical methods and simulations, computational fluid dynamics (CFD), and wind tunnel testing. All these methods produce errors in comparison with real flight conditions; however, research that utilizes FDSMs is carried out under real conditions (Chambers, 2009). FDSMs have been widely used during the creation of new flying vehicles as well as for testing aerodynamic concepts, radical configurations, control systems development, and exploring critical flight envelopes (Jordan et al., 2006; Croom et al., 2000; Sadovnychiy et al., 1998). In addition, FDSMs can allow for the prompt evaluation of concepts in the early design stages (Amadori et al., 2010). Currently, several important projects are underway for developing new technologies and evaluating novel concepts in the field of transport aircraft by means of FDSMs (Cogan & Alley, 2014; Huang, 2015). FDSMs are both geometrically and

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dynamically scaled replicas. Dynamic scaling includes scaling for linear dimensions, weight, inertia, actuator dynamics, and control system responses. The similitude requirements and scaling relationships as applied to FDSM testing have been presented by Wolowicz et al. (1979).

One of the key issues involved in ensuring a dynamic similarity is tuning the mass-inertial parameters of FDSMs (Betin, 2001b; Shakoori et al., 2014). This task can be performed by developing the proper design and arrangement of the components of the model, such as the structure and the systems, during the design process; however, errors are usually produced after the construction of FDSMs. Thus, it is necessary to investigate non-similarities and to tune them (Betin & Ryshenko, 1992; Sarlak, 2014; Shakoori et al., 2015). During the third stage of the FDSM design and development process, the moments of inertia (MI) of the FDSM must be estimated and tuned (Betin, 2001a; Shakoori, 2016). To address this issue, a review of the literature directly related to FDSM mass distribution as well as an extended view of the literature related to distribution and placement problems was conducted (Jordan et al., 2004; Shakoori et al., 2012; Chedrik et al., 2004; Rodi, 2013; Kassem, 2005; Qiu et al., 2012; Malaek & Soltan-Mohammed, 2001). These relevant works investigated the distribution optimization during the design process, which helps solve the problems of current research such as tuning MI. Generally, FDSM is designed and constructed to be light enough to allow for adding ballasts to obtain the desired mass distribution (Burk & Wilson, 1975). Finding a ballast's weight and its position to tune the center of gravity (CG) is straightforward and can be performed using simple equations; however, MI tuning is a relatively sophisticated task. It is important to identify a feasible solution for a ballast's weight and position. In some cases, it is possible to find solutions mathematically, but they are unsuitable for this task (Betin, 2001b; Scherberg & Rhode, 1927).

The purpose of this research was to develop an improved method for MI adjustment that provides accuracy and simplicity. Although several methods have been used to achieve MI adjustment, the new requirements have created an evident need to improve methods for MI tuning. For example, the flexibility of the FDSM configuration to change can reduce the cost and time required for research programs. Due to the issues involved in the extended applications of FDSM, MI tuning methods must be improved. Thus, the National Aeronautics and Space Administration (NASA) ordered dynamically scaled modular aircrafts for flight-based aviation research programs. One of the core capabilities of the ordered FDSMs is the integrated ballast system and the movable payload/avionics racks, which enable tuning mass/inertial properties (2013). In addition, the simplicity and accuracy of installing ballasts are another considerations for defining present study. The proposed method significantly improves MI tuning methods and addresses the issues discussed.

## 2. METHODOLOGY

### 2.1. Main Parameters of FDSM

According to the similarity requirements of the rigid aircraft, the actual ($A$) values of the main parameters of FDSM, i.e., the mass ($m$), center of gravity coordinates ($X, Y, Z$), axial, and product of inertia, must be tuned to the required ($R$) values:

$$(m_M^A, X_{CG}^A, Y_{CG}^A, Z_{CG}^A, I_X^A, I_Y^A, I_Z^A, I_{XY}^A, I_{YZ}^A, I_{ZX}^A) \rightarrow (m_M^R, X_{CG}^R, Y_{CG}^R, Z_{CG}^R, I_X^R, I_Y^R, I_Z^R, I_{XY}^R, I_{YZ}^R, I_{ZX}^R) \quad (1)$$

The moments of inertia and the product of inertia are defined by Equation 2.

$$I_X = \int (y^2 + z^2)dm \ ; I_Y = \int (x^2 + z^2)dm \ ; I_Z = \int (y^2 + x^2)dm$$
$$I_{XY} = \int xydm \ ; I_{YZ} = \int yzdm \ ; I_{ZX} = \int zxdm \tag{2}$$

In addition to the geometrical scale factor, the mass-inertial parameters of the model ($M$) depend on the flight altitude of the model and the full-scale aircraft ($AC$). After the value of the density ratio $k_\rho$ was identified, the required mass-inertial values of the FDSM were calculated using the scale factors of model in Table 1 (Betin & Ryshenko, 1992). Then, during the design process or after construction, the increments for the mass, MI, and PI of the model were calculated using Equation 3 (Betin, 2001b). It is possible to tune the CG location before tuning the MI or to consider the CG position during MI tuning to be a constraint.

Table 1 The scale factors for FDSM

| Parameters | Scale factors |
|---|---|
| Linear dimension | $k_l = l_{AC}/l_M$ |
| Density | $k_\rho = \rho_{AC}/\rho_M$ |
| Mass | $k_m = m_{AC}/m_M = k_\rho k_l^3$ |
| Inertia | $k_I = I_{AC}/I_M = k_\rho k_l^5$ |

$$m_M^R = m_M^A + m_T = \frac{m_{AC}}{k_\rho k_l^3}$$

$$I_{X_M}^R = I_{X_M}^A + \Delta I_{X_M} = \frac{I_{X_{AC}}}{k_\rho k_l^5} \qquad I_{XY_M}^R = I_{XY_M}^A + \Delta I_{XY_M} = \frac{I_{XY_{AC}}}{k_\rho k_l^5}$$
$$I_{Y_M}^R = I_{Y_M}^A + \Delta I_{Y_M} = \frac{I_{Y_{AC}}}{k_\rho k_l^5} \qquad I_{XZ_M}^R = I_{XZ_M}^A + \Delta I_{XZ_M} = \frac{I_{XZ_{AC}}}{k_\rho k_l^5} \tag{3}$$
$$I_{Z_M}^R = I_{Z_M}^A + \Delta I_{Z_M} = \frac{I_{Z_{AC}}}{k_\rho k_l^5} \qquad I_{YZ_M}^R = I_{YZ_M}^A + \Delta I_{YZ_M} = \frac{I_{YZ_{AC}}}{k_\rho k_l^5}$$

where $l$ is length (m), $\rho$ is air density ($kg/m^3$), $k$ is the scale factor of the FDSM's parameters, $\Delta$ is the required value for tuning the MI and PI, and $m_T$ is the required ballast mass for tuning the mass of the FDSM (kg).

### 2.2. Direct Method of MI Tuning

For the direct method, the system of two ballasts with an equal mass, as defined and illustrated in Figure 1, was arranged symmetrically with respect to the origin of the body axes system (Betin, 2001b). The CG position was tuned before tuning the MI. Thus, adding the symmetric ballasts did not alter the position of the CG. In most cases, the aircraft can be considered to be symmetrically located on the XZ plane, and thus the two products of inertia will be zero. In addition, the MI often has more of an effect on aircraft behavior than on PI; thus, in most applications, only the axial MI can be tuned. The explicit solutions for the required ballast weights to tune MI can be obtained by Equation 4 (Betin, 2001b). The positions of the ballasts must be determined by the designer, who must consider the geometrical and technical restrictions of the model. After MI tuning, the total ballast weights must not exceed the allowable value ($m_T$).

$$m_{T_X} = \frac{-\Delta I_X + \Delta I_Y + \Delta I_Z}{2X_T^2}$$
$$m_{T_Y} = \frac{\Delta I_X - \Delta I_Y + \Delta I_Z}{2Y_T^2} \quad (4)$$
$$m_{T_Z} = \frac{\Delta I_X + \Delta I_Y - \Delta I_Z}{2Z_T^2}$$

where $m_{T_X}$, $m_{T_Y}$, and $m_{T_Z}$ are the mass of the ballast on the X, Y, and Z axes, respectively (m), and $X_T$, $Y_T$, and $Z_T$ are the positions of the ballast on the X, Y, and Z-axes, respectively (m).

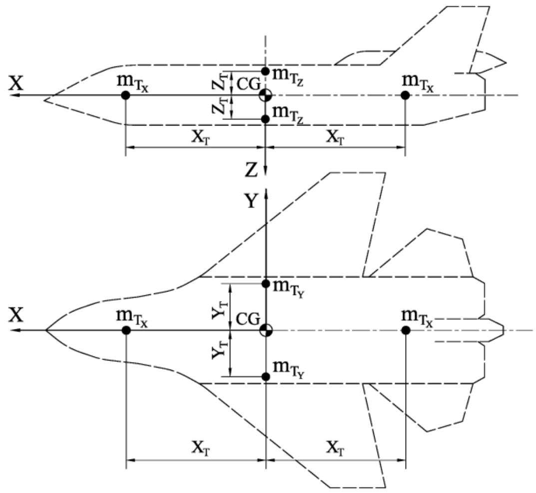


Figure 1 Method of Tuning MI using a system with two symmetrical ballasts

## 2.3. Improved Method for Tuning the MI

The direct method has successfully been used in the development of several FDSMs at the Institute of Physical Modeling of Problems of Aircraft Flight Regimes (NIIPFM) (NIIPFM, 2017); however, for some restrictions, such as geometrical restrictions or the installation of ballasts in the desired position, the improved method is proposed. For this method, the ballasts are located in predefined positions that are feasible for installing ballasts (Figure 2). As shown in Figure 2, a new coordinate system has been defined to determine the positions of the ballasts, but the MI and PI are calculated in the body system. For adding ballasts to the model, six equations for the MI and PI and three equations for the CG must be satisfied. The system of equations is presented in Equation 5. According to the theory of equations, the solution is unique if and only if the rank of system equals the number of variables. If the number of variables are more than the rank of the system of equations, then infinite answers exist. Thus, the consistency of the equation system depends on the FDSM's parameters and the ballasts' locations. As a result, more than nine ballasts were considered when tuning the MI to guarantee a solution. Furthermore, the constraint on the allowable total ballasts' weight was imposed. Hence, the sum of the actual weight of the FDSM plus the ballasts' weights must not exceed the required weight of the FDSM. Due to this constraint, it is probable that a solution will not be found. Nevertheless, for the problems of FDSM design, an incomplete similarity can be accepted by taking certain metrics into account (Betin, 2001a; Shakoori, 2016). Therefore, this problem is converted to an optimization problem in which solutions near optimum are also acceptable (Rosyidi et al., 2016).

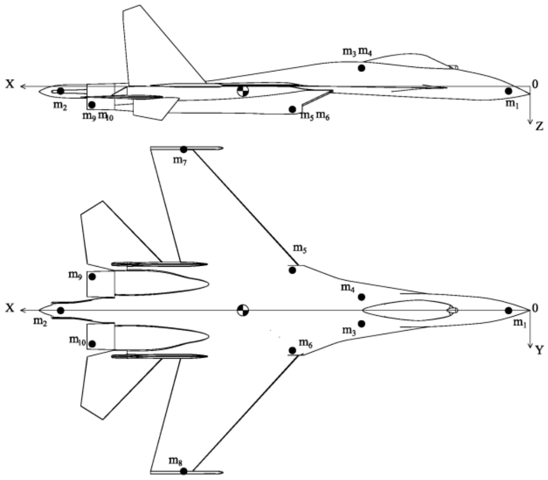


Figure 2 Arrangement of concentrated masses on FDSM of the Su-27 fighter for moments of inertia tuning

Figure 3 18.2% FDSM of the Su-27 fighter on Launcher

$$\begin{cases} \Delta I_{X_M} = \sum_{i=1}^{n} m_i Y_i^2 + m_i Z_i^2 \\ \Delta I_{Y_M} = \sum_{i=1}^{n} m_i X_i^2 + m_i Z_i^2 \\ \Delta I_{Z_M} = \sum_{i=1}^{n} m_i X_i^2 + m_i Y_i^2 \\ \Delta I_{XY_M} = \sum_{i=1}^{n} m_i X_i Y_i \\ \Delta I_{XZ_M} = \sum_{i=1}^{n} m_i X_i Z_i \\ \Delta I_{YZ_M} = \sum_{i=1}^{n} m_i Y_i Z_i \end{cases}$$

$$\begin{cases} X_{CG} = \sum_{i=1}^{n} m_i X_i \Big/ \sum_{i=1}^{n} m_i \\ Y_{CG} = \sum_{i=1}^{n} m_i Y_i \Big/ \sum_{i=1}^{n} m_i \\ Z_{CG} = \sum_{i=1}^{n} m_i Z_i \Big/ \sum_{i=1}^{n} m_i \end{cases} \quad (5)$$

$$\sum_{i=1}^{n} m_i \leq m_T \quad (6)$$

where $m_i$ is mass of $i^{th}$ ballast (kg) and $X_i$, $Y_i$& $Z_i$ are positions of ballast on X, Y, Z-axes, respectively (m).

### *2.3.1. Design variables, objective functions, and constraints*

In this problem, the objective function is the deviation of the actual values of the mass-inertial parameters compared to the required values. The ballast weights were considered design variables. Furthermore, the total weight of the ballasts was defined as a constraint. The constraint was imposed by the exterior penalty function method and added to the objective function to obtain the unconstrained cost-function (Rao, 1979). This problem is a multi-objective optimization that is converted to a single-objective optimization using a linear scalarization technique by Equations 8-9. The weight coefficients of the objectives were estimated and then corrected after running the optimization code.

$$x = (m_1, m_2, m_3, m_4, m_5, m_6, m_7, m_8, m_9, m_{10}) \quad (7)$$

$$F_1(x) = \sum_1^6 w_i \left| I_i^{actual} - I_i^{required} \right|;$$
$$I_1 = I_X;\ I_2 = I_Y;\ I_3 = I_Z;\ I_4 = I_{XY};\ I_5 = I_{XZ};\ I_6 = I_{YZ} \quad (8)$$

$$F_2(x) = w_7 \left| X_{CG}^{actual} - X_{CG}^{required} \right| + w_8 \left| Y_{CG}^{actual} - Y_{CG}^{required} \right| + w_9 \left| Z_{CG}^{actual} - Z_{CG}^{required} \right| \quad (9)$$

$$g(x) = \sum_{i=1}^{10} m_i - m_T \quad (10)$$

$$F(x) = w_{10}F_1(x) + w_{11}F_2(x) + w_{12}(max\{g(x),0\}^2) \quad (11)$$

where $x$ is the design variable vector, $F$ is the cost function, $g$ is the penalty function, $n$ is the number of optimization variables, and $w_i$ are the weighting coefficients.

*2.3.2. Solving algorithm*

The simulated annealing (SA) algorithm was used to solve the optimization problem. This is a permutation problem type because a suitable arrangement of ballasts is the goal. The SA algorithm has a good performance for permutation problems (Dréo et al., 2006). In this algorithm, initialized design variables are considered the starting point. Then, by perturbing the design variables, neighbors are generated, and if the objective function improves, modification will be accepted. Otherwise, it will be accepted with the probability of $e^{-\Delta C/T}$. Here, T is the current temperature, and $\Delta C$ is the objective function change (Dréo et al., 2006; Lobato et al., 2012).

*2.3.3. Case study*

The focus of the study is the MI tuning of the FDSM of a Su-27 fighter airplane (Figure 3), which was developed for research on critical flight regimes, such as post-stall and spin (Cheranovskii, 1997). The mass-inertial parameters of full-scale aircrafts are presented in Table 2 (Betin et al., 2014). Moreover, the altitude of the flight simulation based on the customer request was 5500-6500 m. By using the developed methodology of the FDSM design from the University of Khai, the geometrical scale factor $k_l$ was calculated equal to 5.5. In addition, by choosing the launch method via Jet Assisted Take-off (JATO) and by considering the other technical requirements of FDSM, the flight altitude of the model was calculated to be 570-1650 m. Thus, after identifying $k_l$ and $k_\rho$, the relations in Table 1 can be used to calculate the required values of the mass-inertial parameters of the model.

Table 2 Full-scale aircraft input data for designing FDSM

| | Mass | $\bar{X}_{CG}$ | $I_{XX}$ $(kg.m^2)$ | $I_{YY}$ $(kg.m^2)$ | $I_{ZZ}$ $(kg.m^2)$ | | Min. Altitude $(m)$ | Max. Altitude $(m)$ |
|---|---|---|---|---|---|---|---|---|
| Full-scale | 232.00 | 35.5% | 85370 | 396435 | 473914 | 9438 | 5500 | 6500 |
| Ideal model | 232.96 | 35.5% | 28.31 | 131.5 | 157.2 | 3.2 | 570 | 1650 |
| Actual model | 228.11 | 35.5% | 25.79 | 119.14 | 143.97 | 3.05 | 570 | 1650 |

where $\bar{X}_{CG}$ is the position of the CG relative to the mean aerodynamic chord (MAC).

## 3. RESULTS AND DISCUSSION

To resolve the task of MI tuning of FDSM of Su-27, two methods for tuning, including the direct and improved methods, were used. The direct method has been used in the development of existing FDSMs of Su-27 (Figure 3). Therefore, the performance of the new method was validated by comparing the results with the direct method. Initially, the six symmetric ballasts relative to the CG of the FDSM were determined using Equation 4. Then, the method using ten ballasts on the predefined positions was applied. In the direct method, due to the CG position, which was near the lower surface of the model, using a symmetrical ballast on the Z-axis and in the plane of XOZ was impossible. Thus, only symmetrical ballasts on the X and Y axes were used. These ballasts impacted the entire MI but not the PI. The obtained MI is presented in Table 3, and the errors were calculated in comparison with the required values in Table 2. For the method that used a 8.66 kg ballast, considerable errors were observed in $I_{XX}$ and $I_{XZ}$. For the improved method, Figures 4-7 show the computer code results. The horizontal axes represent the number of temperature changes required to reach the program termination criterion. According to Figure 6, $I_{ZZ}$ was closely converged to the desired value, although $I_{XX}$, $I_{YY}$, and $I_{XZ}$ were not as closely converged to the desired value as $I_{ZZ}$. In such situations, it is possible to increase the importance of one MI or more by changing the weight coefficient of objective functions, considering its effect on the behavior of the FDSM. Due to the nature of the problem, all FDSMs' MI and PI will not converge exactly to the required values. Nevertheless, the results were near the required values, and thus it can be said that the Pareto-optimal solution was obtained. The inability to achieve the global optimum solution could be a result of the limitation of the ballasts' locations within the model surfaces as well as the maximum weight of the ballasts. Hence, in the improved method, the results' convergence to the desired value is better than the first method. The weights and coordinates of the ten ballasts are shown in Table 4. In addition, two ballasts were added to run the program with 12 ballasts. The results in Figures 8–11 show that a considerable improvement was not achieved. Nevertheless, $I_{XX}$ , $I_{YY}$, and $I_{XZ}$ better converged to the required values.

Table 3 Comparison MI after tuning by three methods

| Method | Direct Method | Error % | Improved method with 10 ballasts | Error % | Improved method with 12 ballasts | Error % |
|---|---|---|---|---|---|---|
| Total FDSM mass | 236.77 | 1.64 | 232.79 | -0.07 | 232.80 | -0.07 |
| Total Ballasts mass | 8.66 | -- | 4.86 | -- | 4.85 | -- |
| $I_{XX}$ $(kg.m^2)$ | 27.69 | -2.19 | 27.93 | -1.34 | 28.05 | -0.92 |
| $I_{YY}$ $(kg.m^2)$ | 130.64 | -0.65 | 130.50 | -0.76 | 130.80 | -0.53 |
| $I_{ZZ}$ $(kg.m^2)$ | 157.16 | -0.03 | 157.40 | 0.13 | 157.80 | 0.38 |
| $I_{XZ}$ $(kg.m^2)$ | 3.05 | -4.69 | 3.17 | -0.91 | 3.19 | -0.31 |

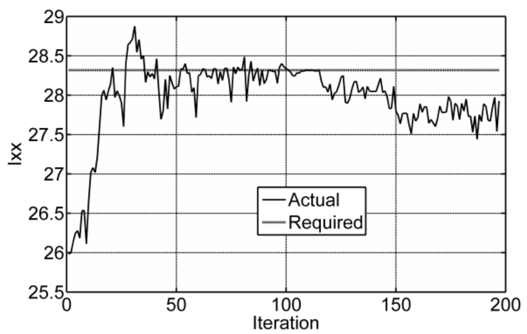


Figure 4 Ixx convergence to required value with 10 ballasts

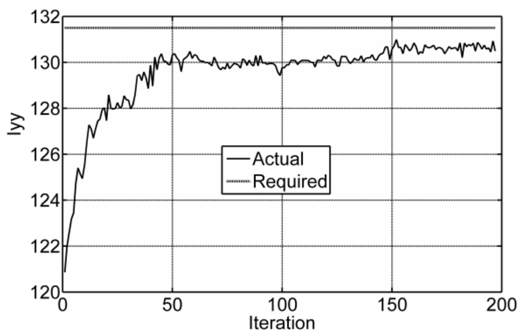


Figure 5 Iyy convergence to required value with 10 ballasts

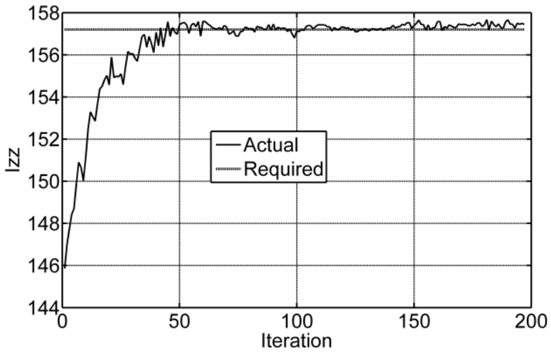


Figure 6 Izz convergence to required value with 10 ballasts

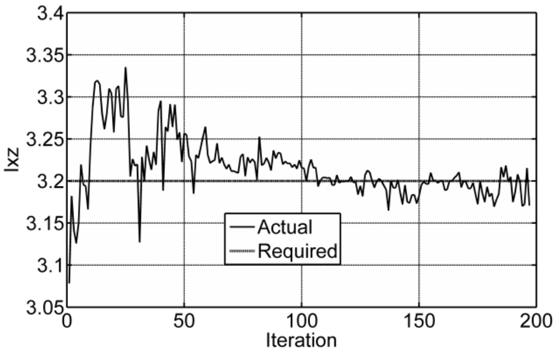


Figure 7 Ixz convergence to required value with 10 ballasts

Table 4 Weights and coordinates of ten ballasts

| Ballast (No.) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Mass (kg) | 1.590 | 1.583 | 0.000 | 0.000 | 0.000 | 0.000 | 0.603 | 0.603 | 0.152 | 0.152 |
| X (m) | 0.175 | 3.800 | 1.370 | 1.370 | 1.930 | 1.930 | 2.800 | 2.800 | 3.555 | 3.555 |
| Y (m) | 0.000 | 0.000 | 0.096 | -0.096 | 0.250 | -0.250 | 1.300 | -1.300 | 0.270 | -0.270 |
| Z (m) | 0.000 | 0.037 | -0.150 | -0.150 | 0.185 | 0.185 | 0.000 | 0.000 | 0.150 | 0.150 |

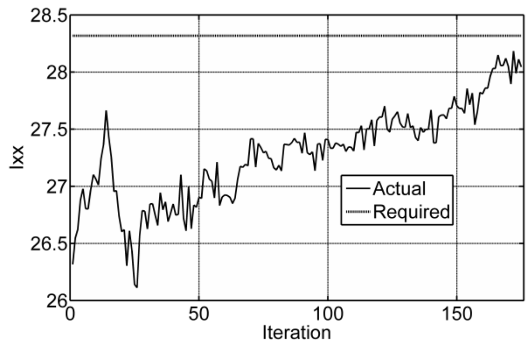


Figure 8 Ixx convergence to required value with 12 ballasts

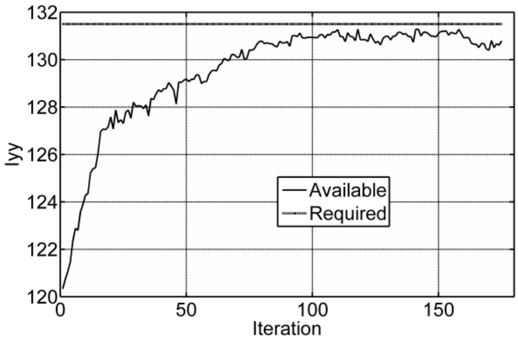


Figure 9 Iyy convergence to required value with 12 ballasts

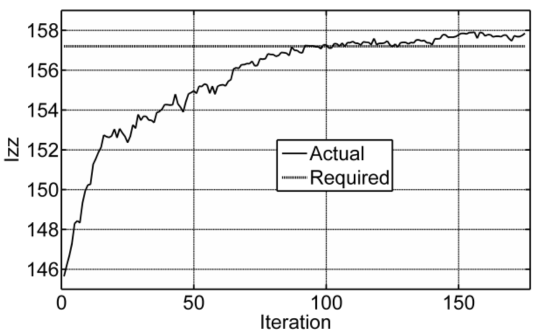


Figure 10 Izz convergence to required value with 12 ballasts

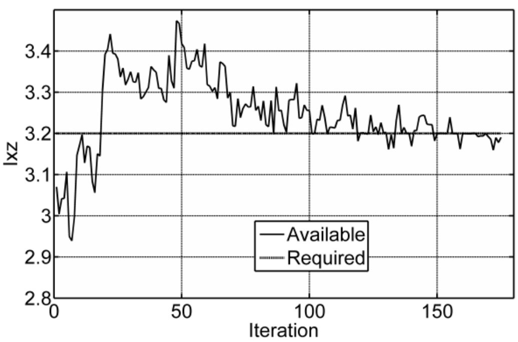


Figure 11 Ixz convergence to required value with 12 ballasts

## 4. CONCLUSION

Tuning of the MI and PI is one of the most critical stages of FDSM design and development. If a similarity between the mass-inertial characteristics is not ensured, the constructed model will be useless and can lead to considerable financial losses. In the current study, the existing methods were evaluated. Furthermore, the method of MI tuning by a system of symmetrical ballasts was investigated in detail. Then, a novel method was developed based on previous experience and new requirements. A practical example was solved for the existing FDSM using the direct and improved methods. The proposed method improved the ability to tune the MI compared to previous methods. In addition, another advantage of this method is the possibility of defining the feasible and easy-access positions for the installation of ballasts. Moreover, using metaheuristic optimization algorithms, such as SA, helped identify solutions even if the solutions were Pareto-optimal. Finally, the applications of the method can be extended to more complex problems, such as dynamic similarity satisfaction in various configurations and flight regimes.

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