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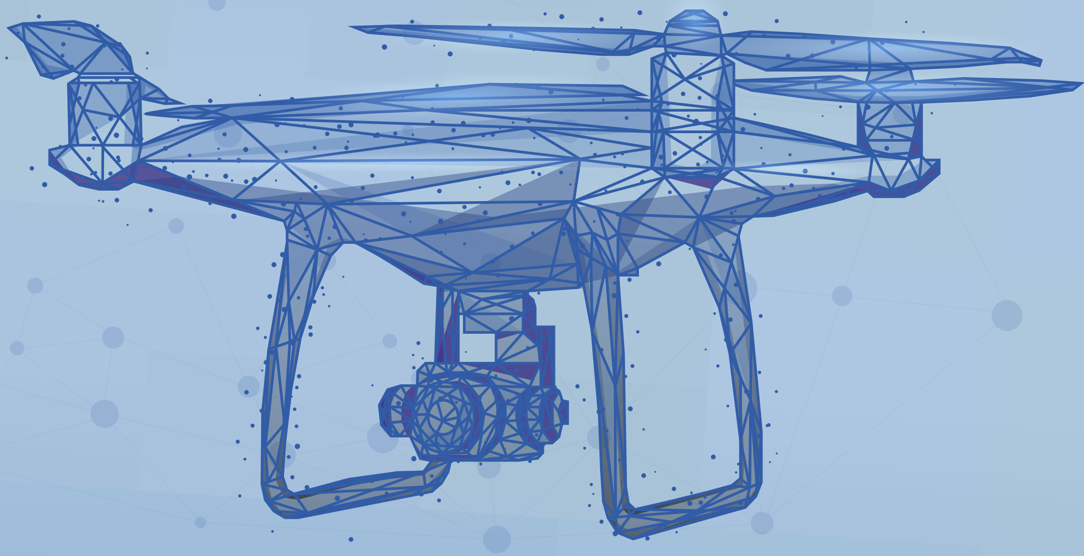

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Research Article

Accuracy in Determining Aircraft Position by Terrestrial Radio Navigation

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Abstract

The main objective of terrestrial radio navigation is position determination. In this study, the accuracy of the distance measurement, distance difference measurement, and integrated angle measurement/distance measurement terrestrial radio navigation methods is investigated. in order to calculate the position errors, simulations for the aircraft flight dynamics were carried out, and the obtained position values were compared with the actual values. The aircraft position determination methods were evaluated in the sense of accuracy. The position determination method with better accuracy was determined by comparing the absolute errors of the examined methods. Simulation and error analysis shows that the distance difference method is superior and gives more accurate position results. It was observed that the distance measurement method errors were smaller than the errors of the integrated angle measurement/distance measurement method.

Keywords

Aircraft
Position determination
Distance measurement
Distance difference measurement
Line of positions
Terrestrial radio navigation

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1. Introduction

Terrestrial navigation includes dead reckoning (DR), visual navigation (VN), radio navigation (RN), and some other methods of positioning. These methods are used on land, at sea, and in aviation.

The main objective of terrestrial radio navigation is position determination. Special radio navigation systems provide information on directions, angles, distances, pseudo ranges, and combinations of these types of information.

The radio navigation systems require a technically complex design of a large set of tall antennas and expensive infrastructure (Bhardwaj, 2020). Most radio navigation systems depend on measurement or determining in some way the distance from the known location to the current location of the recipient.

The global terrestrial-based navigation systems include Alpha, developed by the *Union of Soviet* Socialist Republics (USSR; Alpha, 2020), and Omega, developed by the United States of America (USA) (Omega, 2020). Omega uses the intersection of Line of Positions (LOPs) using distance measurements to determine the user's position. For providing higher accuracy of the receiver, a minimum of three or more independent distance measurements can be used (Bhardwaj, 2020).

LORAN-A (long-range navigation system) is a hyperbolic regional terrestrial-based radio navigation system developed in the USA. This system determines the receiver's position by calculating the time of arrival difference between the signals of the master and slave stations (Bhardwaj, 2020). The regional terrestrial-based navigation system LORAN-B, developed in the United States, provides an accuracy of the order of several tens of feet (LORAN, 2020).

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The proposal to transition from terrestrial-based navigation aids to satellite and aerial surveillance as a primary means of navigation is presented (Blakey, 2006). From this point on, the Global Positioning System (GPS) is considered the main navigation method in terrestrial and oceanic travel.

LORAN-C is the terrestrial-based navigation system which is developed by the USA (LORAN, 2020). Loran-C is a more successful system, and attempts are being made to integrate into solution positioning, navigation, and timing (PNT) services together with satellite navigation systems. LORAN-C support can correct the global navigation satellite systems (GNSS) uncertainties against jamming (Gluch et al., 2000).

In terrestrial radio navigation, a VHF omnidirectional range (VOR) and distance measuring equipment (DME) are used widely. The VOR allows the receiver to measure its bearing to or from the beacon. DME is defined as a navigation beacon to measure the aircraft position relative to that beacon. Aircraft send out a signal which is sent back after a fixed delay by the DME hardware. The aircraft can compute its distance to the beacon from the delay of the signal received by the DME instruments (Krinetskiy 1977; Haciyev, 1999).

An aircraft's position in space is defined by three coordinates. In radio navigation, for aircraft's position characteristics, the surface of positions (SOPs) and line of positions are used. The aircraft's position is defined by two position lines or three-position surfaces or by position line and position surface. As a navigation parameter, elevation angle, azimuth angle, distance, distance difference, or sum of distances can be used (Krinetskiy 1977; Kayton and Fried, 1997).

In general, when three geometric surfaces cross, there are a few intersecting points (Hajiyev, 1999). In this case, there may be several solutions for determining the aircraft's position. This problem can be avoided by using extra information for each position.

The error analysis in determining aircraft coordinates by the distance measurement method is given in (Hacıyev and Üner, 1998). In (Erkal and Hacıyev, 2004), the accuracy of the distance difference measurement method is investigated. However, these studies do not compare different types of terrestrial radio navigation techniques.

In this study, the accuracy of the distance measurement, distance difference measurement, and integrated angle measurement/distance measurement terrestrial radio navigation methods is investigated using simulations. For this purpose, the aircraft flight dynamics are simulated, and the obtained values of the coordinates were compared with the actual values. The aircraft position determination method with better accuracy was determined by comparing the absolute errors of the examined methods.

2. Mathematical Model of Aircraft Dynamics

The mathematical model of the aircraft's motion consists of longitudinal and lateral motion models. The longitudinal motion of the aircraft consists of forwarding, vertical, and pitching motions. The state vector X_u and control vector U_u of the longitudinal model can be written in the following form:

$$X_u = [u \ \ w \ \ q \ \ \theta]^T$$

$$u = [\delta_E]$$

where

u : forward velocity of the aircraft (m/s)

w : vertical velocity of the aircraft (m/s)

q : pitching rate of the aircraft (degree/s)

θ : pitching angle of the aircraft (degree)

δ_E : elevator deflection (degree)

The mathematical model of the longitudinal motion is given by the following differential equation,

$$\dot{X}_u = A_u X_u + B_u U_u \tag{1}$$

where Au is the system matrix, Bu is the control distribution matrix. These matrices are (McLean, 1990):

$$A_u = \begin{bmatrix} X_u & X_w & 0 & -g\cos\gamma_0 \\ Z_u & Z_w & U_0 & -g\sin\gamma_0 \\ \widetilde{M}_u & \widetilde{M} & \widetilde{M} & \widetilde{M}_\theta \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{2}$$

$$B_u = \begin{bmatrix} X_{\delta_E} \\ Z_{\delta_E} \\ \widetilde{M}_{\delta_E} \\ 0 \end{bmatrix} \tag{3}$$

The lateral motion of the aircraft consists of sideslip, roll, and yaw motions. The state vector X_y and control vector U_y of the lateral model can be written as:

$$X_y = [\beta \ \ p \ \ r \ \ \varphi \ \ \psi]^T$$

$$u = \begin{bmatrix} \delta_A \\ \delta_R \end{bmatrix}$$

where

β : sideslip angle of the aircraft (degree)

p : rolling rate of the aircraft (degree/s)

r : yawing rate of the aircraft (degree/s)

φ : rolling angle of the aircraft (degree)

ψ : yawing angle of the aircraft (degree)

δ_A : aileron deflection angle (degree)

δ_R : rudder deflection angle (degree)

The mathematical model of the lateral motion is given by

$$\dot{Z}_y = A_y X_y + B_y U_y \quad (4)$$

where the system matrix Ay and the control distribution matrix by are (McLean, 1990):

$$A_y = \begin{bmatrix} Y_v & 0 & U_0 & g\,cos_{\gamma_0} & 0 \\ L'_v & L'_p & L'_r & 0 & 0 \\ N'_v & N'_p & N'_r & 0 & 0 \\ 0 & 1 & tan_{\gamma_0} & 0 & 0 \\ 0 & 0 & sec_{\gamma_0} & 0 & 0 \end{bmatrix} \quad (5)$$

$$B_y = \begin{bmatrix} 0 & Y_{\delta_R} \\ L'_{\delta_A} & L'_{\delta_R} \\ N'_{\delta_A} & N'_{\delta_R} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (6)$$

For small side slip velocities, $v = U_0\beta$ assumption can be made. Notations in (2), (3), (5), and (6) can be found in (McLean, 1990).

Additional expressions must be included in the model to determine the positions along X, Y and Z directions:

$$\dot{x} = u \quad (7)$$

$$\dot{y} = v = U_0\beta \quad (8)$$

$$\dot{z} = w \quad (9)$$

The state vector of the mathematical model of aircraft is,

$$X = [u\ w\ q\ \theta\ \beta\ p\ r\ \phi\ \psi\ x\ y\ z]^T$$

The control vector of the system is,

$$U = [\delta_E \delta_A \delta_R]^T$$

Discretizing the aircraft's mathematical model, we have

$$X = AX + BU \Rightarrow X_i = \frac{X_{i+1} - X_i}{\Delta t} = AX_i + BU_i,$$

$$X_{i+1} - X_i = A\Delta t.X + B\Delta t.u_i,$$

$$X_{i+1} = \underbrace{(I + \Delta tA)}_{A^*} X_i + \underbrace{\Delta t.BU_i}_{B^*} \Rightarrow$$

$$X_{i+1} = A^* X_i + B^* U_i \quad (10)$$

where X is the aircraft state vector, A^* is the system matrix, U is the control input vector, B^* is the control distribution matrix

3. Determination of Aircraft's Coordinates Via Distance Measurement Method

In the distance measurement method, the position surface is a sphere with radius D which is the distance from the station to the aircraft. Thus, an aircraft's position in a space can be found by intersecting three D=const position surfaces. The intersection of the three spheres is shown in Figure 1.

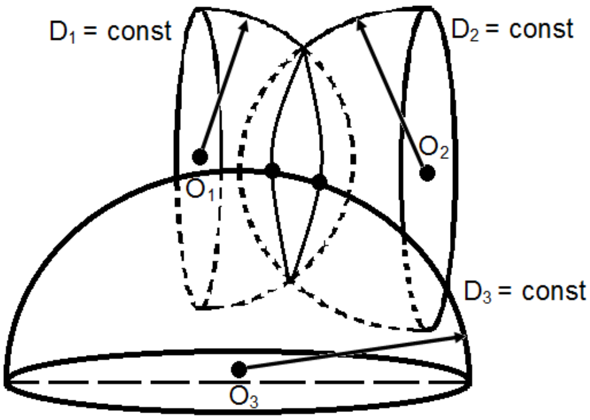

Fig.1. The intersection of three spheres

Since there are two intersection points when intersecting three spheres, the results of this method are uncertain. To make this method more precise, it can be integrated with extra navigation systems with low accuracy.

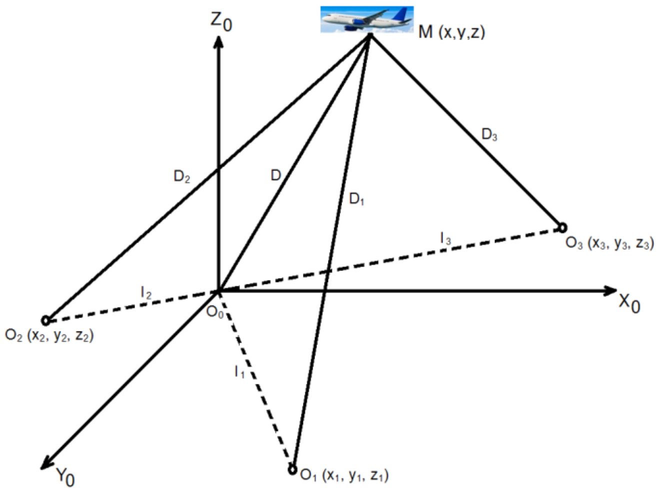

Fig. 2. Distance measurement method's scheme in determining the position of the aircraft

Three measurement stations (distance measurement stations) are located on the ground to determine the aircraft's position. Let us assume that the ground stations located on $O_1(x_1,y_1,z_1)$, $O_2(x_2,y_2,z_2)$, and $O_3(x_3,y_3,z_3)$ points of $O_0X_0Y_0Z_0$ Descartes coordinate system to find calculation formulas of distance measurement method (See Fig. 2). l_1, l_2 and l_3 show the distance between the ground station's origins and the origin of $O_0X_0Y_0Z_0$ coordinate system, and D_1, D_2, and D_3 show the distances to the aircraft at $M(x,y,z)$ point. The equations for the coordinate determination can be written as (Haciyev, 1999):

$$(x_1 - x_2)x + (y_1 - y_2)y + (z_1 - z_2)z = c_1 \quad (11)$$

$$(x_1 - x_3)x + (y_1 - y_3)y + (z_1 - z_3)z = c_2 \quad (12)$$

$$(x_2 - x_3)x + (y_2 - y_3)y + (z_2 - z_3)z = c_3 \quad (13)$$

Here

$$c_1 = \frac{1}{2}(D_2^2 - D_1^2 + l_1^2 - l_2^2) \quad (14)$$

$$c_2 = \frac{1}{2}(D_3^2 - D_1^2 + l_1^2 - l_3^2) \quad (15)$$

$$c_3 = \frac{1}{2}(D_3^2 - D_2^2 + l_2^2 - l_3^2) \quad (16)$$

The solution of equations (11)-(13) for aircraft coordinate determination can be found as follows (Sametoğlu and Hajiyev 2021):

$$x = e_1 - az; \quad (17)$$

$$y = e_2 - bz; \quad (18)$$

$$(a^2 + b^2 + 1)z^2 + 2(x_1 a - z_1 + y_1 b - ae_1 - be_2)z - (D_1^2 - l_1^2 - e_1^2 - e_2^2 + 2x_1 e_2) = 0 \quad (19)$$

where

$$e_1 = \frac{c_1(y_2-y_3)-c_3(y_1-y_2)}{(x_1-x_2)(y_2-y)-(x_2-x_3)(y_1-y)}; \quad (20)$$

$$e_2 = \frac{c_1(x_1-x_3)-c_3(y_1-y_2)}{(x_1-x_2)(y_1-y)-(x_1-x_2)(y_1-y_3)}; \quad (21)$$

$$\mathrm{a} = \frac{(z-z_2)(y_2-y)-(z_2-z)(y_1-y)}{(x_1-x_2)(y_2-y)-(x_2-x_3)(y_1-y)}; \quad (22)$$

$$\mathrm{b} = \frac{(z_1-z_2)(x_2-x_3)-(x_1-z)(x_1-x_2)}{(x_1-x_3)(y_1-y_2)-(x_1-x_2)(y_1-y)}; \quad (23)$$

4. Determination of Aircraft Coordinates Via Distance Difference Measurement Method

In distance difference measurement, radio-navigation systems, the distances from two ground stations to aircraft are taken as navigation parameters (Krinetskiy 1979). Measurement of ΔD distance differences allow to determine that the aircraft locates on $\Delta D = constant$ state surface. This surface is in the form of rotating hyperboloids of the two-leaf stage, which has measurement stations on O and O_1 centers (Figure 3).

The aircraft's position is found as the intersection point of three state surfaces. Therefore, the distance-difference measurement radio-navigation system includes four ground stations. One of these stations is the router (main station), and the others are directed (assistant stations). With the help of signals sent by the main station, three directed stations are provided to work synchronously. With the distance-difference method, we derive the following expressions and get x, y and z coordinates of an aircraft:

$$x_1 x + y_1 y + z_1 z - D\Delta D_1 = f_1 \quad (24)$$

$$x_2 x + y_2 y + z_2 z - D\Delta D_2 = f_2 \quad (25)$$

$$x_3 x + y_3 y + z_3 z - D\Delta D_3 = f_3 \quad (26)$$

here,

$$\Delta D_1 = D - D_1 \quad (27)$$

$$\Delta D_2 = D - D_2 \quad (28)$$

$$\Delta D_3 = D - D_3 \quad (29)$$

are the range differences.

$$f_1 = \frac{1}{2}(l_1^2 - \Delta D_1^2) \quad (30)$$

$$f_2 = \frac{1}{2}(l_2^2 - \Delta D_2^2) \quad (31)$$

$$f_3 = \frac{1}{2}(l_3^2 - \Delta D_3^2) \quad (32)$$

Via solving (24) - (26) equations, the expressions required for the aircraft coordinates x, y, z are found.

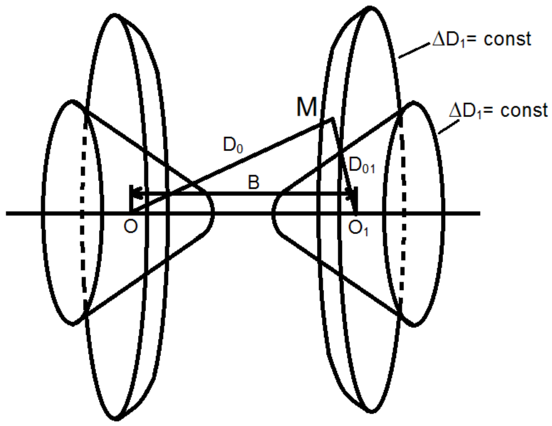

Fig.3. Illustration of the state surfaces in the distance difference measurement method.

5. Determination of Aircraft's Coordinates by Integrated Method

Measurement of angle and measurement of distance methods are used at the same time in the integrated method (Haciyev, 1999). The integrated method is usually used in radiolocation systems, and it determines D distance to the aircraft, azimuth angle α, and elevation angle β. When this method is used, the coordinates of the aircraft are determined as the intersection point of the sphere state surface (D=constant), cone state surface (β=constant), and vertical plane suitable for α =constant state surface (Fig. 4). The aircraft coordinates are determined with a single point (ground station) with the help of this method without the need for difficult calculations.

Following formulas are used to calculate aircraft coordinates;

$$x = D\cos\beta\cos a$$
$$y = D\cos\beta\sin a \quad (33)$$
$$z = D\sin\beta$$

Distance, azimuth, and elevation angles are determined by radiolocation measurements. A single radiolocation station is enough for this method

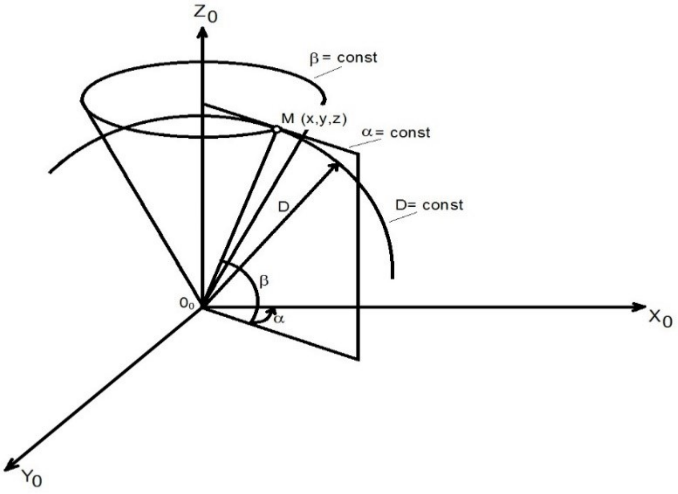

Fig.4. Illustration of the state surfaces in the integrated method.

6. Simulation Results and Discussion

The distance measurements are simulated via the equation below:

$$D_{z_i} = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} \quad (34)$$
$$+b + \sigma_D \text{randn}$$

where x_i, y_i and z_i are the coordinates of the ground radio-navigation stations, b is the bias in the distance measurements, σ_D is the standard deviation of random distance measurement error, which is $\sigma_D = 10\,\text{m}$ in simulations.

The simulations are performed for the azimuth angle α and elevation angle β via the expressions below;

$$a = ArcTan\left[\frac{Y}{X}\right];$$
$$\beta = ArcTan\left[\frac{Z}{X} cosa\right] \quad (35)$$

Matlab software was used to investigate the accuracy of terrestrial radio navigation methods through simulations.

The simulation results and error analysis show that the distance difference method gives more accurate position results. The absolute errors of the distance-difference measurement method along the x, y, and z axes are given in Fig. 5, 6, and 7, respectively.

The aircraft position error analysis led to the result that the distance difference method is more accurate for horizontal x and y coordinates while it is not as much as good for the vertical z coordinate. As seen from the graphs, the absolute errors of horizontal x and y coordinates are good and varies approximately within the limits of [-25; +25] meters. The disadvantage of this method is that 4 ground stations are required for implementation.

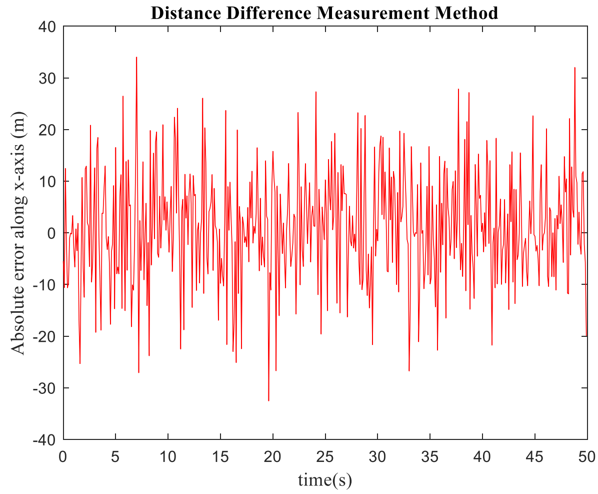

Fig. 5. Absolute error along the x-axis when using the distance difference measurement method.

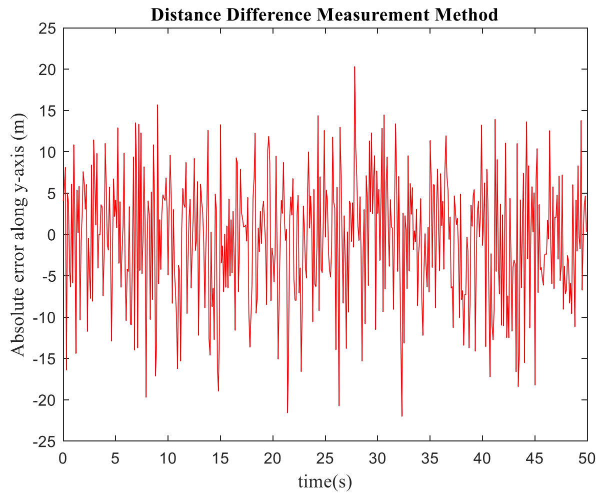

Fig.6. Absolute error along the y-axis when using the distance difference measurement method.

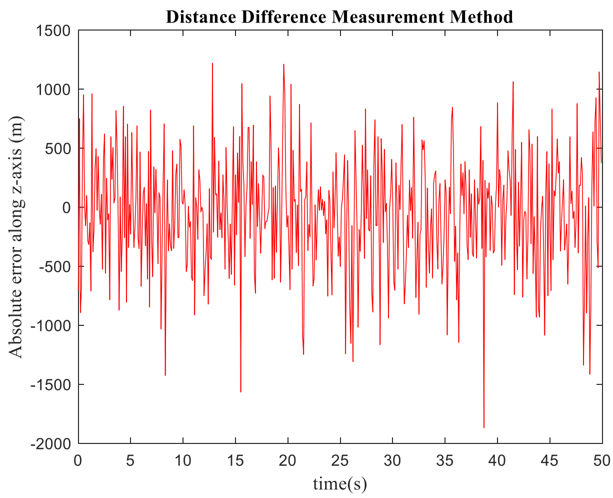

Fig.7. Absolute error along the z-axis when using the distance difference measurement method.

The relative errors of the distance-difference measurement method along the x, y and z axes are presented in Figs. 8, 9, and 10, respectively.

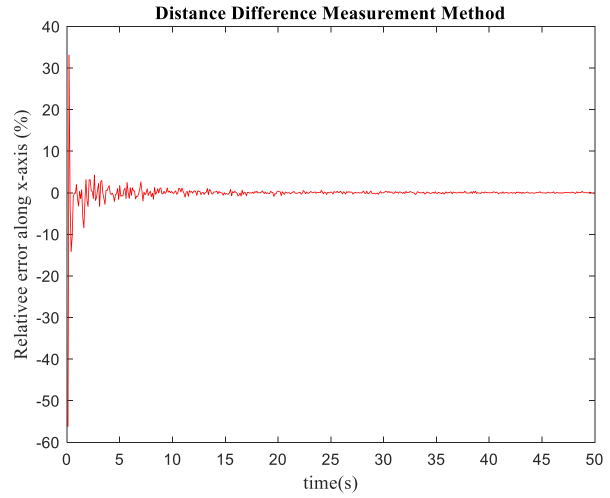

Fig. 8. Relative error along the x-axis when using the distance difference measurement method.

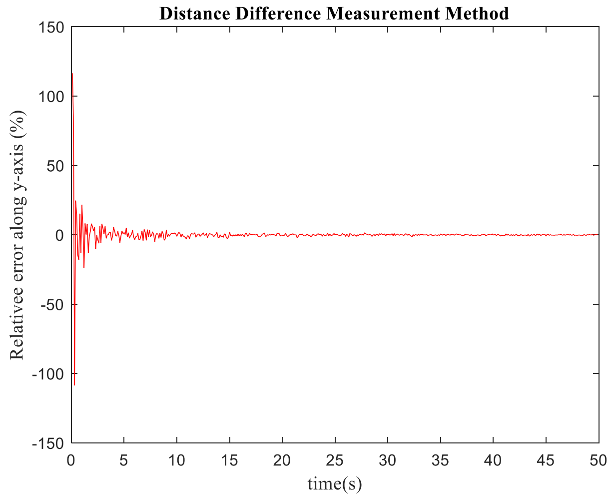

Fig. 9. Relative error along the y-axis when using the distance difference measurement method.

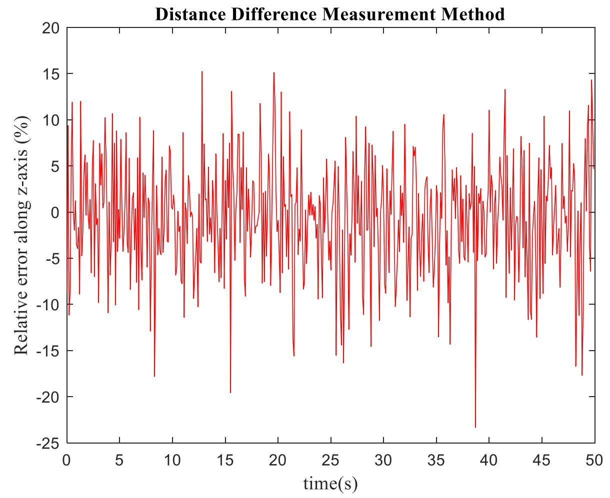

Fig. 10. Relative error along the z-axis when using the distance difference measurement method.

The results shown in Figures 8, 9, and 10 show that the relative errors in the x and y coordinates are good enough but high on the z-axis.

Simulation results are also obtained for distance measurement and integrated methods. The obtained results show that the errors calculated in the distance measurement method are smaller than the errors found in the integrated angle measurement/distance measurement method. As a result, calculating the aircraft coordinates with the distance measurement method is more advantageous than the integrated method. However, to implement the distance measurement method, three ground stations are required, whereas only one station is necessary for the integrated method.

The integrated method requires only one ground station, but the position determination accuracy deteriorates as the aircraft moves away from that station. The simulation results presented in Figure 11, showing absolute errors along the y-axis when using the integrated method, confirm this statement.

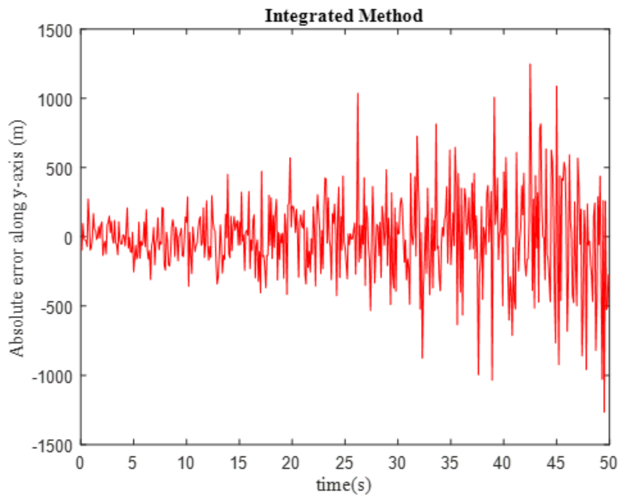

Fig. 11. Absolute error along the y-axis when using the integrated method.

7. Combination of Terrestrial and Satellite-Based Navigation Systems

The study (Bhardwaj, 2020) shows that there is a large potential for the combined navigation solutions from terrestrial and Satellite-based navigation systems.

In the case of satellite navigation methods, the main limitation arises in closed areas such as dense forest and tunnel areas or underground areas where local solutions such as radio frequency identification (RFID) or wireless local area networks (LANs) provide indoor location tracking systems are available (Chothani et al., 2015). Thus, it is necessary to combine the two methods and provide a more reliable system, overcoming the limitations of existing terrestrial and satellite navigation systems (Bhardwaj, 2020).

Recently developed regional systems include the Quasi-Zenith Satellite System (QZSS) developed in Japan and the Indian Regional Navigation Satellite System (IRNSS).

Global and regional satellite navigation systems provide their services with an accuracy of about 10–20 meters. A literature review presented in (Bhardwaj, 2020) shows that regional satellite navigation systems such as IRNSS and QZSS provide accuracy comparable to GNSS in their main service region.

Terrestrial radio navigation systems can include the same kinds of faults as GNSS. The terrestrial radio signals can be subject to multipath, while interference or signal attenuation can affect all or some signals at a given location. These problems can cause many receivers to produce a stream of false measurements prior to detecting signal unavailability. The user equipment can also include hardware or software failures (Groves, 2008).

8. Conclusion

In this study, the accuracy of the different terrestrial radio navigation methods is investigated. The distance measurement, distance difference measurement, and integrated angle measurement/distance measurement aircraft position determination methods are taken into consideration. Simulations were carried out for aircraft flight dynamics. The position values that are determined by the presented methods were compared with the actual values.

Simulation and error analysis led to the result that the distance difference method is superior and gives more accurate position results. It was observed that the distance measurement method errors were smaller than the errors of the integrated method.

The demonstrations also show that the examined aircraft position determination methods are more accurate in determining the horizontal x and y coordinates than the vertical z coordinate determination.

There is a good potential for the combined navigation solutions of terrestrial and satellite-based navigation systems.

CRediT Author Statement

Chingiz Hajiyev: Conceptualization, Methodology, Investigation, Validation, Supervision, Writing-Original Draft. **Alper Mehdi Sametoğlu:** Writing-Review, Investigation, Software, Visualization.

Abbreviations

DME	: Distance measuring equipment
DR	: Dead Reckoning
GNSS	: Global Navigation Satellite Systems
GPS	: Global Positioning System
IRNSS	: Indian Regional Navigation Satellite System
LANs	: Local Area Networks
LOPs	: Line of Positions
LORAN	: Long-Range Navigation System
PNT	: Positioning, Navigation and Timing
QZSS	: Quasi-Zenith Satellite System
RFID	: Radio-Frequency Identification
RN	: Radio Navigation
SOPs	: Surface of Positions
USA	: United States of America
USSA	: Union of Soviet Socialist Republics
VN	: Visual Navigation
VOR	: Omnidirectional range

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International Journal of Aviation Science and Technology

Research Article

Identification and Stochastic Optimizing the UAV Motion Control in Turbulent Atmosphere

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Abstract

In a class of diffusion Markov processes, we formulate a problem of identification of nonlinear stochastic dynamic systems with random parameters, multiplicative and additive noises, control functions, and the state vector at a final time moment. For such systems, the identifiability conditions are being studied, and necessary conditions are formulated in terms of the general theory of extreme problems. The developed engineering methods for identification and optimizing nonlinear stochastic systems are presented as well as their application for unmanned aerial vehicles under wind disturbances caused by atmospheric turbulence, namely, for optimizing the autopilot parameters during a rotary maneuver of an unmanned aerial vehicle in translational motion, taking into account the identification of its angular velocities.

Keywords

Unmanned Aerial Vehicle
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1. Introduction

Stochastic differential and discrete models are applied in the study of complex controlled systems under conditions of random parametric, structural, and external disturbances.

The mathematical foundations for such researches are presented in well-known monographs by Bulinsky and Shiryaev, 2005; Evlanov and Konstantinov, 1976; Fleming and Rishel, 1975; Gikhman and Skorokhod, 1977; Kazakov, 1977; Oksendal, 2000; Solodov and Solodov, 1988 et al. . Here and further, we apply for the alphabetical citation order.

Strict mathematical methods for optimizing nonlinear systems are also known; for example, Dubovitskii and Milyutin, 1965; Girsanov, 1970; Ioffe and Tikhomirov, 1974; Kazakov and Artemyev, 1980; Kolosov, 1984 et al..

In the applied theory of optimizing nonlinear stochastic systems, approximate methods based on parametric or functional approximation of the a posteriori probability distribution density are used. Parametric approximation methods are applied to determine the characteristics of stochastic processes, namely, a posteriori moments or cumulants, which are usually called semi-invariants, see the monographs by Bodner et al., 1987; Chernetsky, 1968; Denisov and Rodnishchev, 2017; Dostupov, 1970; Kozhevnikov, 1978; Malakhov, 1978; Potseluyev, 1984; Pugachev and Sinitsyn, 1985 et al..

Our theoretical results on this topic were presented in research papers (Rodnishchev, 2001a,b; Rodnishchev and Khairullin, 2010). These results were implemented in the Russian aerospace industry, namely in control

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systems of spacecraft (Rodnishchev et al., 2019), including mini-satellites for communication (Fig. 1) and the Earth-observing (Fig. 2), space robot-manipulators (SRMs), Fig. 3 (Somov et al. l., 2019), as well as Russian passenger airliners, Fig. 4 (Rodnishchev and Somova, 2019), in control systems of turboprop engines for various aviation equipment (Bodner et al., 1987; Kozhevnikov et al., 1989).

In this paper, methods for identification in stochastic control systems and study the problem of optimizing parameters of unmanned aerial vehicle (UAV) autopilot during its turning maneuver in translational movement under stochastic atmospheric turbulence are briefly presented.

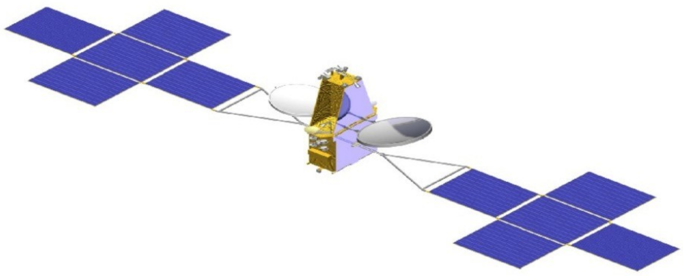

Fig. 1. The communication mini-satellite

Fig. 2. The Earth-surveying mini-satellite

2. Models and the Problem Statement

In this section, the problem of identifying vectors of parameters $\mathbf{a} \equiv \{a_i\} \in \mathrm{R}^m$ and control $\mathbf{u} \equiv \{u_i\} \in \mathrm{R}^r$ is studied for nonlinear stochastic system

$$dy_i = (\Sigma C_{ij}(t,\mathbf{b})dt + dw_{ij}(t))\,\phi_{ij}(t,\mathbf{y},\mathbf{b},\mathbf{u},\mathbf{a})) + \Sigma\sigma_{ij}(t,\mathbf{y},\mathbf{b})\,d\eta_j(t),\ i \in \mathrm{N}_1^n,\ \ t \in [t_{\mathrm{i}}, t_{\mathrm{f}}] \tag{1}$$

with a state vector $\mathbf{y} = \{y_i\} \in \mathrm{R}^n$ at initial condition $\mathbf{y}_{\mathrm{i}} = \{y_{\mathrm{i}i}\}$ where $\mathrm{N}_1^n \equiv [1,2,\ldots n]$ and observations

$$z_k = \Sigma c_{k\nu} y_\nu + \dot{w}_k(t),\ k \in \mathrm{N}_1^p. \tag{2}$$

Identification efficiency is evaluated by functional minimum

$$I_0(\mathbf{u},\mathbf{a}) = \int_{t_{\mathrm{i}}}^{t_{\mathrm{f}}} E[\Sigma\alpha_k(z_k - \Sigma c_{k\nu} y_\nu)^2]\,dt, \tag{3}$$

and control objectives, technical and operational requirements to the system are determined by constraints on the final system status of the equality type

$$I_s(\mathbf{u},\mathbf{a}) = E[f_s(\mathbf{y}_{\mathrm{f}})] - c_s = 0, \quad s \in \mathrm{N}_1^q. \tag{4}$$

Here $E[\cdot]$ is the expectation operator, t_{i} and t_{f} are the initial and final points of a time interval and $\mathbf{y}_{\mathrm{f}} = \{y_{\mathrm{f}i}\} = \mathbf{y}(t_{\mathrm{f}})$.

As a control vector $\mathbf{u}(\cdot)$, we study a program control $\mathbf{u}(t)$ or feedback control $\mathbf{u}(t,\mathbf{y})$. Control $\mathbf{u}(t)$ is determined on the set $\mathrm{S} = \{\mathbf{u}(t) \in L_2[t_{\mathrm{i}}, t_{\mathrm{f}}] : \mathbf{u}(t)\} \in U, t \in [t_{\mathrm{i}}, t_{\mathrm{f}}]\}$, where $L_2[t_{\mathrm{i}}, t_{\mathrm{f}}]$ is the space of measurable functions with quadratic metrics and $U \subset \mathrm{R}^r$ is a convex set.

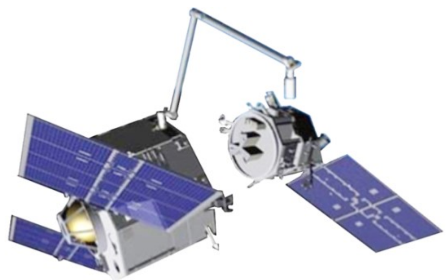

Fig. 3. The SRM is preparing to capture a failed satellite

Fig. 4. Russian passenger airliner IL 96-300 on landing

The feedback control $\mathbf{u}(t,\mathbf{y})$ is considered as Borelian function as either a random element in L_2 or a non-anticipating process relative to Wiener processes w_{ij}, η_j with values in U.

Next, column $\mathbf{a}$ determinate the controlling parameters; $\mathbf{b} \equiv \{b_i\} \in \mathrm{R}^l$ is a random vector; $w_{ij}(t) = W_{ij}(t)\,dt$ and $\eta_j(t) = \mathrm{N}_j(t)\,dt$ are Stratonovich stochastic differentials of Wiener processes $w_{ij}(t)$ and $\eta_j(t)$, moreover, the process $w_{ij}(t)$ describes multiplicative noises affecting the system, the process $\eta_j(t)$ describes additive noises, $W_{ij}(t)$ are white Gaussian noises that describes random internal perturbations common for the system, $\mathrm{N}_j(t)$ are the white Gaussian noises; $C_{ij}(t,\mathbf{b})$, $\phi_{ij}(t,\mathbf{y},\mathbf{b},\mathbf{u},\mathbf{a})$ and $\sigma_{ij}(t,\mathbf{y},\mathbf{b})$ are given nonrandom functions satisfying given requirements of solution existence (1), and $\mathbf{z} \equiv \{z_k\} \in \mathrm{R}^p$ is observed vector of tester coordinates $z_k, k \in \mathrm{N}_1^p, p \le n$. The matrix component $(c_{k\nu})$ determines the selection of observed system coordinates (1), $\dot{w}_k(t)$ is derivative of Wiener process, $w_k(t)$ is component $R_k(t)$ of tester additive white noise.

At last, $I_s(\mathbf{u},\mathbf{a})$ are continuous and continuously differentiable functionals on a set of variables, and $I_0(\mathbf{u},\mathbf{a})$ is bounded functionally differentiable on the set of variables and α_k are the weight numbers.

At accepted conditions concerning the right parts, solution (1) exists, and it is unambiguous. However, this solution does not need to be a Markov process. That is why, to make (1) describe the Markov process, we introduce an extended state vector $\mathbf{x} \equiv \{x_i\} = \{\mathbf{y},\mathbf{b}\}$. Relative to the state vector $\mathbf{x}$ equations (1) reduce themselves to an equivalent system of diffusion stochastic differential equations

$$\begin{aligned} dx_i &= (\Sigma C_{ij}(t,\mathbf{x})\,dt + dw_{ij}(t))\,\phi_{ij}(t,\mathbf{x},\mathbf{u},\mathbf{a})) \\ &\quad + \Sigma \sigma_{ij}(t,\mathbf{x})\,d\eta_j(t), \quad x_i(t_\mathrm{i}) = y_{\mathrm{i}i} \ \ \forall i \in \mathrm{N}_1^n; \\ dx_i &= 0, \qquad\qquad x_i(t_\mathrm{i}) = b_i \quad \forall i \in \mathrm{N}_{n+1}^{n+l}. \end{aligned} \tag{5}$$

These equations have a single solution and describe the diffusion Markov process $\forall t \in [t_\mathrm{i}, t_\mathrm{f}]$; the posterior density of state probability $p(t,\mathbf{x}\,|\,\overline{\mathbf{z}})$ satisfies the Stratonovich-Kushner equation (a generalization of the well-known Fokker-Planck- Kolmogorov equation)

$$\partial p(\cdot)/\partial t = L(\cdot)p(\cdot) + (F(\cdot) - \textstyle\int F(\cdot)p(\cdot)\,d\,\mathbf{x})\;p(\cdot) \tag{6}$$

with $\mathbf{x} \in \Omega \subset \mathrm{R}^n$ and initial condition $p(t,\mathbf{x}\,|\,\overline{\mathbf{z}})|_{t=t_\mathrm{i}} = p(t_\mathrm{i},\mathbf{x})$. Here $F(\cdot) = F(\mathbf{x},\mathbf{z})$ and $L(\cdot)p(\cdot) = L(t,\mathbf{x},\mathbf{u},\mathbf{a})\,p(t,\mathbf{x}\,|\,\overline{\mathbf{z}})$ is an elliptic operator determined by the formula

$$L(\cdot)\,p(\cdot) = -\Sigma\partial[A_i\,p(\cdot)]/\partial x_i + (1/2)\Sigma\partial^2[B_{ip}\,p(\cdot)]/\partial x_i \partial x_p \tag{7}$$

with coefficients of the drift $A_i = A_i(t,\mathbf{x},\mathbf{u},\mathbf{a})$ and diffusion $B_{ip} = B_{ip}(t,\mathbf{x},\mathbf{u},\mathbf{a})$. In the density function, $p(t,\mathbf{x}\,|\,\overline{\mathbf{z}})$ the vector $\overline{\mathbf{z}}$ means that the whole output signal realization of the tester observed on the time interval $t \in [t_\mathrm{i}, t_\mathrm{f}]$ is applied.

Assume that G_{pk} are the mutual forces of tester noises and $F(\mathbf{x},\mathbf{z}) = \Sigma(c_{pq}x_q/G_{pk})(z_k - (1/2)\Sigma c_{k\nu}x_\nu)$ scalar function characterize the tester properties. According to a theory of Markov processes, original identification problem (1) – (3) concerning the extended vector of system state $\overline{\mathbf{x}} = \{\mathbf{x}, x_{n+1}\}$ reduces itself to an equivalent terminal problem with distributed parameters relative to a posterior density function $p(t,\overline{\mathbf{x}}\,|\,\overline{\mathbf{z}})$ in the form

$$I_0(\mathbf{u},\mathbf{a}) = \textstyle\int x_{n+1}\,p(t_\mathrm{f},\overline{\mathbf{x}}\,|\,\overline{\mathbf{z}})\,d\,\overline{\mathbf{x}} \ \Rightarrow \ \min; \tag{8}$$

$$\partial p(\cdot)/\partial t = \bar{L}(\cdot)p(\cdot) + (F(\cdot) - \textstyle\int F(\cdot)p(\cdot)\,d\,\overline{\mathbf{x}})\;p(\cdot) \tag{9}$$

with $F(\cdot) = F(\overline{\mathbf{x}},\mathbf{z})$ and the condition $p(t,\overline{\mathbf{x}}\,|\,\overline{\mathbf{z}})|_{t=t_\mathrm{i}} = p(t_\mathrm{i},\overline{\mathbf{x}})$;

$$I_s(\mathbf{u},\mathbf{a}) = \textstyle\int f_s(\mathbf{x})\,p(t_\mathrm{f},\overline{\mathbf{x}}\,|\,\overline{\mathbf{z}})\,d\,\overline{\mathbf{x}} - c_s = 0, \quad s \in \mathrm{N}_1^q. \tag{10}$$

Here the component $x_{n+1}(t)$ is determined by equation

$$d\,x_{n+1} = \Sigma\alpha_k(z_k - \Sigma c_{k\nu}x_\nu)^2\,dt \equiv g(\mathbf{x})\,dt \tag{11}$$

with initial condition $x_{n+1}(t_\mathrm{i}) = 0$ and the operator

$$\bar{L}(\cdot)p(\cdot) \equiv L(\cdot)p(\cdot) - \partial[g(\mathbf{x})p(t,\overline{\mathbf{x}}\,|\,\overline{\mathbf{z}})]/\partial x_{n+1}.$$

This model is identifiable if the system (5), (11) is controllable (Rodnishchev, 2001a; Denisov and Rodnishchev, 2017).

The main objectives of this paper are a brief presentation of our general approach to the considered problem and its practical application to optimizing the UAV autopilot parameters at its route turning under the turbulent wind perturbations.

3. Method and the Approach

For obtaining the necessary identification conditions in terms of conjugate cones in the general theory of extreme problems (Dubovitskii and Milyutin, 1965; Ioffe and Tikhomirov, 1974), the method by Girsanov (1970) is applied.

In this case, the solution to the equation (6) is needed as well as the coupled Bellman parabolic equation. However, as it is known, analytic solutions to linear and special cases of nonlinear stochastic systems only can be obtained. Here our approach (Rodnishchev, 2001) is applied, which is based on employing mathematical statistics.

The identification problem with respect to a posteriori semi invariant is reduced to the equivalent extreme problem of the estimation parameters, control, and components of the state vector in the form

$$\begin{aligned} &\omega_1^{n+1}(t_\mathrm{f}) \Rightarrow \min, \\ &\dot{\omega}_1^{n+1} = E[\Sigma\alpha_k(z_k - \Sigma c_{k\nu}x_\nu)^2], \quad \omega_1^{n+1}(t_\mathrm{i}) = 0; \end{aligned} \tag{12}$$

$$\dot{\omega}_1^j = E[A_j(\cdot)] + E[x_j F(\mathbf{x},\mathbf{z})] - \omega_1^j E[F(\mathbf{x},\mathbf{z})] \equiv g_1^j,$$
$$\dot{\omega}_{11}^{jp} = E[(x_j - \omega_1^j)A_p + (x_p - \omega_1^p)A_j + E[B_{jp}(\cdot)]$$
$$+ E[(x_j - \omega_1^j)(x_p - \omega_1^p)F(\mathbf{x},\mathbf{z})] - \omega_{11}^{jp} E[F(\mathbf{x},\mathbf{z})],$$
$$\dot{\omega}_2^j = 2E[(x_j - \omega_1^j)A_j(\cdot)] + E[B_{jj}(\cdot)]$$
$$+ E[(x_j - \omega_1^j)^2 F(\mathbf{x},\mathbf{z})] - \omega_2^j E[F(\mathbf{x},\mathbf{z})],$$
$$\ldots\ldots\ldots$$
$$\dot{\omega}_{N_j}^j = N_j E[(x_j - \omega_1^j)A_j^{N_j-1}(\cdot)] + (1/2)N_j(N_j-1)$$
$$E[(x_j - \omega_1^j)^{N_j-2} B_{jj}(\cdot)] - \Sigma_{q_j=1}^{N_j-2} C_{N_j}^{q_j} g_{q_j}^j \omega_{N_j-q_j}^j$$
$$+ E[(x_j - \omega_1^j)^{N_j} F(\mathbf{x},\mathbf{z})] - \omega_{N_j}^j E[F(\mathbf{x},\mathbf{z})] \quad (13)$$

for $N_j \geq 3$ with initial conditions

$$\omega_1^j(t_i) = c_{1i}^j,\ \omega_{11}^{jp}(t_i) = b_{11i}^{jp},\ \omega_2^j(t_i) = b_{2i}^j,\ \ldots,\ \omega_{N_j}^j(t_i) = b_{N_j i}^j$$

and indexes $j, p \in \mathrm{N}_1^n$, also taking into account (10).

The equations (13) present variations of semi-invariants ω_1^j of the 1-st order by j-th components for the system state vector, coinciding with the mathematical expectations; semi-invariants ω_2^j and ω_{11}^{jp} of 2-nd order by j-th components and the relationship between j-th and p-th components, coinciding with the dispersion and correlation functions of the state vector; at last, semi-invariants $\omega_{N_j}^j$ of the N_j-th order.

For the closure of a shortened system of differential equations (13) and an approximate representation of the higher moments through the lower moments, the method of moment semi-invariants is applied (Dashevskii, 1976).

Assume $N_j = 8$, that is sufficient to solve practical problems. Semi-invariants are not independent, and they are bound by the conditions for the functions $f_\mu, \mu \in \mathrm{N}_1^9$ (Malakhov, 1978):

$$f_1 = 2(\omega_2^j)^2 + \omega_4^j \geq 0; \qquad f_2 = 2\omega_2^j \omega_2^p + \omega_{22}^{jp} \geq 0;$$
$$f_3 = a\,\omega_2^j(\omega_2^p)^2 + \omega_{24}^{jp} \geq 0; \quad f_4 = a(\omega_2^j)^2 \omega_2^p + \omega_{42}^{jp} \geq 0;$$
$$f_5 = a(\omega_2^j)^2 + \omega_6^j \geq 0; \qquad f_6 = b(\omega_2^j)^2(\omega_2^p)^2 + \omega_{44}^{jp} \geq 0;$$
$$f_7 = b\,\omega_2^j(\omega_2^p)^3 + \omega_{26}^{jp} \geq 0; \quad f_8 = b(\omega_2^j)^3 \omega_2^p + \omega_{62}^{jp} \geq 0;$$
$$f_9 = b(\omega_2^j)^4 + \omega_8^p \geq 0, \text{ where } a = 105 \text{ and } b = 166214.$$

These functional inequalities should be performed in the solution of the optimization problem (12), (13) on the time interval $t \in [t_i, t_f]$, so that is the functions f_μ must belong to an integral variety $f_\mu \geq 0$ for the set of differential equations

$$(d f_\mu(t)/dt)|_{(13)} = -\rho f_\mu [1 + \mathrm{sign}(f_\mu)]/2, \quad \mu \in \mathrm{N}_1^9 \qquad (14)$$

with $\rho > 0$, $\mathrm{sign}(0) = 0$, $f_\mu(t_f) \geq 0$ when $f_\mu(t_i) = 0$ $\forall \mu \in \mathrm{N}_1^9$.

4. Optimizing the UAV Autopilot Parameters

This section solves the problem of stochastic optimization of autopilot parameters for the UAV turn mode, taking into account the identification of UAV angular velocities in atmospheric turbulence.

At an angular velocity $\omega_y^{\#} = \mathrm{const}$, the UAV lateral angular motion is described in standard notations by the equations

$$\dot{\beta} = k_\gamma \gamma + k_\beta(\beta + \beta_w) + \alpha_o \omega_x + \omega_y;$$
$$\dot{\omega}_x = -L_\beta(\beta + \beta_w) + L_\delta \delta - L_x \omega_x - L_y \omega_y - l_e i_y^e \omega_y^{\#};$$
$$\dot{\omega}_y = -N_\beta(\beta + \beta_w) - N_x \omega_x - N_y \omega_y;$$
$$\dot{\gamma} = \omega_x; \quad \dot{\psi} = \omega_y; \quad \dot{\delta} = \omega_y - \omega_y^{\#};$$
$$\dot{\beta}_w = -q_x \beta_w + \sigma_{\beta_w} \sqrt{2 q_x}\, N(t), \qquad (15)$$

where $q_x = V_o / L_{w_x}$ with a nominal true airspeed V_o of the UAV flight and a scale L_{w_x} of turbulence; $\sigma_{\beta_w} = \sigma_{\omega_x}/V_o$ with the root mean square (RMS) value σ_{ω_x} of the turbulence intensity, $N(t)$ is standard white noise, and α_o is the UAV balancing angle of attack. Here we use the following notations

$$L_\beta = l_\beta + l_e i_\beta^e;\ L_x = l_{\omega_x} + l_e i_x^e;\ L_\delta = l_e q_e;\ L_y = l_{\omega_y} - l_e i_y^e;$$
$$N_\beta = n_\beta + n_d i_\beta^d; \quad N_x = n_{\omega_x} + n_d i_x^d; \quad N_y = n_{\omega_y} - n_d i_y^d,$$

where $k_\gamma, k_\beta, l_\beta, l_{\omega_x}, l_{\omega_y}, l_e, n_\beta, n_{\omega_x}, n_{\omega_y}, n_d$ are the UAV aerodynamic coefficients, and $i_\beta^e, i_x^e, i_y^e, q_e, i_\beta^d, i_x^d, i_y^d$ are the autopilot gear ratios.

To determine variations of the additional sliding angle β_w, we use a model for the horizontal wind turbulence components, which describes a Gaussian random process with a spectral density $S(\omega) = (2/\pi)\,\sigma_{\omega_x}^2 L_{w_x} / (1 + \omega^2 L_{w_x}^2)$, and when using the formative filter (Pugachev and Sinitsyn, 1985), it is represented by a stochastic differential equation in (15) with the input noise $N(t)$.

The autopilot gear ratios are linearly related to the coefficients $L_x, L_y, L_\delta, N_\beta, N_x, N_y$ of the stochastic system (15), so the definition of the ratios $i_\beta^e, i_x^e, i_y^e, q_e, i_\beta^d, i_x^d, i_y^d$ is reduced to the optimization of these coefficients with the angular velocity measurements $z_1 = \omega_x + N_{\omega_x}, z_2 = \omega_y + N_{\omega_y}$, where the vector $\mathbf{z} \equiv \{z_1, z_2\}$ N_{ω_x} and N_{ω_y} are standard white noises.

The effectiveness of the linear control law optimization is estimated the functional minimum

$$I_0 = \int_{t_i}^{t_f} E[(\omega_y - \omega_y^{\#})^2]\, dt \Rightarrow \min . \tag{16}$$

Since wind disturbances caused by horizontal gusts can lead to large deviations when turning the UAV, the parameters of control law are determined so that coefficients $C_i, i \in \mathrm{N}_1^5$ of the characteristic polynomial for the closed-loop system (15) provide a consistent choice of parameters from the asymptotic stability region.

With the notation, $q \equiv \alpha_o / k_\gamma$ this region has the boundary defined by the following constraints:

$$L_x^3 - C_1 L_x^2 + C_2 L_x - (C_3 - C_4 q + C_5 q^2) = 0;$$
$$L_x + N_y - (C_1 - k_\beta) = 0;\ k_\gamma L_y N_\beta + (C_4 - C_5) q = 0;$$
$$L_x N_y + N_\beta - (C_2 - k_\beta (C_1 - k_\beta)) = 0;\ k_\gamma L_\delta N_\beta - C_5 = 0.$$

To solve the optimization problem, the additional variable $x_8(t)$ is introduced, which is determined by the solution of the differential equation

$$\dot{x}_8 = (\omega_y - \omega_y^{\#})^2$$

with the initial condition $x_8(t_i) = 0$, and the functional (16) is reduced to the following terminal form

$$I_0 = E[x_8(t_f) \Rightarrow \min . \tag{17}$$

Thus, the problem of optimizing the autopilot gear ratios is reduced to determining the vector column

$$\mathbf{a} \equiv \{a_i, i \in \mathrm{N}_1^6\} \equiv \{L_x, L_y, L_\delta, N_\beta, N_x, N_y\}$$

with a providing of the minimum terminal functional (17) and taking into account the need for identification of the angular velocities ω_x and ω_y to the above restrictions on asymptotic stability region.

The system (15) describes a diffusion on Markovian process with the state vector $\mathbf{x} = \{x_i\} \equiv \{\beta, \omega_x, \omega_y, \gamma, \psi, \delta, \beta_w\}$, the coefficients of drift

$$A_1 = -k_\beta (x_1 + x_7) + \alpha_o x_2 + x_3 + k_\gamma x_4;$$
$$A_2 = -a_1 x_2 - a_2 (x_3 - \omega_y^{\#}) + a_3 x_6 - l_{\omega_x} \omega_y^{\#};$$
$$A_3 = -a_4 (x_1 + x_7) - a_5 x_2 - a_6 x_3;\ A_4 = x_2;$$
$$A_5 = x_3;\ A_6 = x_3 - \omega_y^{\#};\ A_7 = -q_x x_7;\ A_8 = (x_3 - \omega_y^{\#})^2$$

and diffusion $B_{77} = 2\sigma_{\omega_x}^2 q_x$. Here, for identification of the above angular velocities, the scalar function

$$F(\mathbf{x}, \mathbf{z}) = x_2 (z_1 - x_2/2)/G_{\omega_x} + x_3 (z_2 - x_3/2)/G_{\omega_y}$$

is applied. So, the stochastic problem is reduced to the deterministic one for the semi-invariants as follows

$$\omega_8^1(t_f) \Rightarrow \min; \tag{18}$$

$$\dot{\omega}_1^j = E[A_j(\cdot)] + E[x_j F(\mathbf{x}, \mathbf{z})] - \omega_1^j E[F(\mathbf{x}, \mathbf{z})],$$
$$\dot{\omega}_{11}^{jp} = E[(x_j - \omega_1^j) A_p + (x_p - \omega_1^p) A_j$$
$$+ E[(x_j - \omega_1^j)(x_p - \omega_1^p) F(\mathbf{x}, \mathbf{z})] - \omega_{11}^{jp} E[F(\mathbf{x}, \mathbf{z})],$$
$$\dot{\omega}_2^j = 2E[(x_j - \omega_1^j) A_j(\cdot)] + E[B_{jj}(\cdot)]$$
$$+ E[(x_j - \omega_1^j)^2 F(\mathbf{x}, \mathbf{z})] - \omega_2^j E[F(\mathbf{x}, \mathbf{z})] \tag{19}$$

$\forall j, p \in \mathrm{N}_1^7$, taking into account the above restrictions on the asymptotic stability region. Equations (18), (19) are ordinary differential equations of order 36 with respect to semi-invariants ω_8^1 and ω_1^j, ω_2^j, ω_{11}^{jp} with indexes $j, p \in \mathrm{N}_1^7$.

5. The Simulation Results and Discussion

The dynamics of the UAV turn with a mass of 320 kg was studied, taking into account wind disturbances caused by atmospheric turbulence. At the flight altitude $H = 1000$ m with airspeed $V_o = 111$ m/s and the balancing angle of attack $\alpha_o = 3.9$ deg, the UAV aerodynamic coefficients have the following values (Romanenko et al., 2012):

$$k_\beta = 0.1946;\ k_\gamma = 0.0833;\ l_\beta = 47.272;$$
$$l_{\omega_x} = 6.776;\ l_{\omega_y} = 1.742;\ l_e = 176.54;$$
$$n_\beta = 13.81;\ n_{\omega_x} = 0.108;\ n_{\omega_y} = 0.859;\ n_d = 7.12.$$

Moreover, coefficients of the characteristic polynomial providing stability have the values

$$C_1 = 14, C_1 = 69.9, C_3 = 213, C_4 = 217, C_5 = 120.$$

In this case, the UAV autopilot ratios are equal to the values

$$i_\beta^e = -0.268;\ i_x^e = 0.0093;\ i_y^e = 0.611;\ q_e = 0.58;$$
$$i_\beta^d = -0.132;\ i_x^d = -0.0152;\ i_y^d = 0.628, \tag{20}$$

which correspond to the following coefficients $a_i, i \in \mathrm{N}_1^6$

$$a_1 = L_x = 8.42;\quad a_2 = L_y = -106.2;$$
$$a_3 = L_\delta = 102.3;\quad a_4 = N_\beta = 12.85;$$
$$a_5 = N_x = 0;\quad a_6 = N_y = 5.39.$$

The problem of optimization (18), (19) with restrictions at the turbulence scale $L_{w_x} = 310$ m is solved with the specified height and the RMS value $\sigma_{\omega_x} = 2.8$ m/s for turbulence of the wind, which corresponds to the "strong" turbulence according to the European airworthiness standards. As a result of solving the optimization problem with identifying the UAV angular velocities by the proposed approach, the coefficients $a_i, i \in N_1^6$ were obtained with the values

$$a_1 = L_x = 8.91; \quad a_2 = L_y = -109.6;$$
$$a_3 = L_\delta = 99.3; \quad a_4 = N_\beta = 14.125;$$
$$a_5 = N_x = 0; \quad a_6 = N_y = 4.83,$$

which correspond to the autopilot gear ratios with the following values:

$$i_\beta^{e} = -0.268;\ i_x^{e} = 0.0121;\ i_y^{e} = 0.631;\ q_e = 0.56; \\ i_\beta^{d} = 0.045;\quad i_x^{d} = -0.0152;\quad i_y^{d} = 0.55. \qquad (21)$$

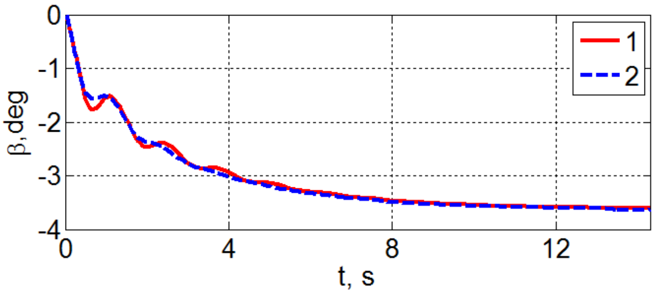

Fig. 5. The changing average values of angle β

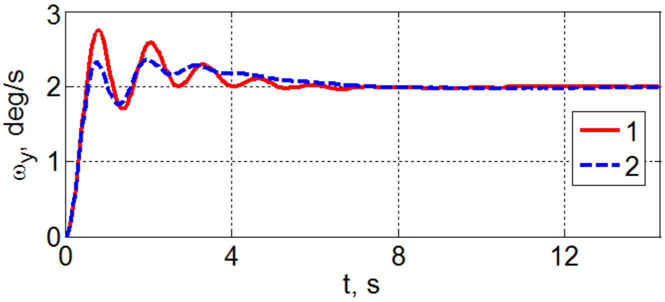

Fig. 6. The changing average values of angular rate

The transients corresponding to the initial values of the autopilot gear ratios (20) are shown in Figs. 5 – 8 in continuous graphs (**1**, red). The transients corresponding to optimized values of the autopilot gear ratios (21), taking into account the wind turbulent disturbances and identification of the angular velocities, ω_x, ω_y are presented in the same figures by dashed graphs (**2**, blue).

The presented data clearly demonstrate that the UAV autopilot parameters synthesized, taking into account wind effects, on average, provide a parry of disturbances caused by atmospheric turbulence, and reduce the amplitude of damped oscillations in the transient processes.

6. Conclusions

Elaborated methods for identification of the parameters and control functions of nonlinear stochastic systems with perturbations, noises, and functional equality type constraints are presented. Important applications relating to optimizing the parameters of the UAV autopilot during its rotational maneuver in translational motion when the turbulent wind disturbances, taking into account the identification of the UAV angular velocities, are briefly represented. The article's main breakthroughs are as follows:

(i) For random controlled processes, a fast calculation of semi-invariants is performed with the necessary accuracy. The results are applied for recurrent parametric optimization on the specified criteria;

(ii) The developed algorithms were implemented in contemporary computer-aided technology of designing UAVs.

Abbreviations

RMS	:	Root Mean Square
SRM		Space Robot-manipulator
UAV	:	Unmanned Aerial Vehicle

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Research Article

Monitoring System of Vibroacoustic Parameters of a Working Zone

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Abstract

This article discusses the safety problems of the use of aviation technology associated with the influence of operational vibration of aircraft. The topical issue of timely detection and prevention of a dangerous state of critical machines and mechanisms is analyzed. Modern means of measuring vibration parameters, principles of measurement, as well as characteristics of the sensitive element of the measuring transducer, are considered. The block diagram and operation algorithm of the proposed system for monitoring vibroacoustic parameters, which is built on the basis of a piezoelectric transducer, is presented. This system can measure the parameters of noise and vibration and analyze the measured data, signal about exceeding the permissible ranges for human work, display the measured data. The advantage of the proposed system is the connection of the measuring channels with the mainboard using the Bluetooth module, which allows the sensors to measure noise and vibration to be placed in any part of the working area.

Keywords

Vibration
Noise
Measurement
System
Vibration sensors

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1. Introduction

At present, the state of flight safety remains at a rather low level, since every year there are aviation accidents with the loss of equipment and human lives. Flight safety is largely determined by the reliability of all units (Tomaszek H et al., 2010). Modern aircraft have a large number of units, devices, systems, instruments, with the help of which automatic and automated control of steering surfaces, landing gear, power plant, communication and navigation facilities, radar, life support systems for the crew and passengers, etc. is carried out (Advanced Avionics Handbook). The complexity and importance of the tasks solved with the help of the aircraft include the automation of onboard systems with a high degree of survivability, safety, reliability, and efficiency of operation. Along with the quantitative growth and expansion of application opportunities, aviation science and industry are faced with the task of significantly improving the technical and economic characteristics of aircraft.

Improvement of control systems of modern aircraft with various automatic devices posed difficult tasks for designers to ensure flight safety in the event of a failure of these devices. The aircraft control system must provide control in all flight modes with the required accuracy. The continuous increase in the number of functions performed by automatic devices is accompanied by an increase in various types of sensors, converters, calculators, actuators, and other elements of automatic equipment. This, in turn, makes high demands on the parts of aircraft units.

One of the methods of ensuring the compliance of the technical condition of aircraft with the strength requirements, the accepted norms, and rules is the identification of structural and technological defects of the airframe, units, and systems. The solution to the problem of monitoring defects in the structures of

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aircraft and spacecraft is achieved by the results of vibration tests (Berns et al., 2019) (Abdulameer et al., 2015). Such tests are modal control tests of aircraft and dynamic tests, which are an integral part of their ground experimental testing.

When developing new objects of technology, dynamic tests in the process of developing machines, which makes it possible to identify design flaws, and to ensure the safety and quality of its operation, it is necessary to carry out control procedures, diagnostics, and protection, which requires accurate measurements, registration, and analysis of qualitative processes (vibration and shock signals).

Today, it is impossible to name almost a single object of control or production process that would not be affected by vibration, shock, or acoustic loads. The study of oscillatory processes is of great interest for all sectors of the national economy - metallurgy, power engineering, rocket technology, etc. Breakdowns in aviation and space technology are associated with fatigue changes in products under the influence of periodic vibration loads (Berns et al., 2019) (Abdulameer et al., 2015). Therefore, the most common of all types of testing is vibration exposure with a frequency sweep.

Analysis of publications devoted to this topic made it possible to compile a list of defects and establish the causes and consequences of their occurrence. For example, in (Motylev. 2004) (Perera et al., 2009), the appearance of cracks and destruction in a structure is judged by the change in its natural frequencies, forms, and decrements of vibrations. In (Postnov. 2000), to detect damage, it is proposed to use the correction of the inertia and structural stiffness matrices based on changes in the natural frequencies of the system due to the appearance of defects. A method for detecting local damage to composite structures by changing natural frequencies and damping parameters corresponding to various modes of vibration was developed (Perera et al., 2009).

It becomes urgent to solve the problem of further development of methods and creation of devices for recording, analyzing, and controlling dynamic processes to improve the quality of dynamic tests, vibration diagnostics, and vibration protection of machines and equipment at the stage of development and operation. Therefore, in the course of the work, a review and analysis of modern means of measuring vibration and noise according to the vibroacoustic parameters of the working area were carried out. The actual task of design and research of the system of monitoring of vibroacoustic parameters of the working zone in which the influence of vibration and noise parameters is present is set.

2. Methods

Today, the number of devices and ancillary equipment measuring vibroacoustic parameters is in the hundreds of types. They differ in accuracy, cost, and availability of different functionality. To ensure the safety of the operation of equipment, it is necessary to carry out periodic diagnostics, which makes it possible to identify incipient malfunctions of machines long before the moment when the failure becomes inevitable, that is, to ensure the operation of equipment according to its technical condition. Due to the huge information capacity of vibroacoustic processes accompanying the operation of machines and the use of computer technology, the requirement to improve the quality and reliability of the operation of machines brings to the fore the methods of vibration diagnostics. Analysis of works in the field of vibration diagnostics (Stakhoca et al., 2021) (Guo et al., 2009) showed that the overwhelming majority of works are devoted to the analysis of the process of generating vibration signals by machine defects, the formation of a reference spectrum and methods for comparing the reference and current spectra. At the same time, in order to improve the quality of vibration diagnostics, especially when diagnosing incipient defects, it is necessary to develop new approaches for developing devices for recording, analyzing, and controlling dynamic processes that improve the quality of dynamic tests, vibration diagnostics, and vibration protection of machines and equipment at the development and operation stage.

When studying vibration parameters, two measurement principles are used - kinematic and dynamic. The kinematic principle is that the coordinates of the points of the object under study are measured relative to the selected fixed coordinate system. The dynamic principle is based on measuring the parameters of the vibration process relative to a stationary frame of reference, in most cases, the centre of gravity of the inertial element of the sensor. In other words, the dynamic principle of vibration measurement is ensured through the use of an inertial mass fixed on an elastic suspension, which, at sufficiently high vibration frequencies, keeps the inertial element practically at rest.

The described measurement principles can be implemented using contact and non-contact vibration measurement methods. When practically any (except induction) vibration sensors are used, the output signals from them do not exceed several tens of millivolts. Therefore, the output of the sensor is connected to the device for amplifying and normalizing the measurement information signal.

2.1. Sensors for measuring vibration parameters

At this time, most measurements of vibration processes are carried out using sensors of vibration accelerations (accelerometers) (Varanis et al., 2018) (Faisal et al., 2020), and the acceleration is converted into vibration velocity, vibration by electrical methods. This article provides an example of developing a system for measuring vibration parameters using a piezo accelerometer. The device will measure vibration displacement, vibration speed, and vibration acceleration. Another difference is the ability to transmit measurement results over distance. The combination of analog and digital parts allows us to create a device relevant for today, both economically and technically.

The shape and frequency composition of vibration processes is determined by the nature of the excitation forces and the transmission of these excitations to the place where the primary measuring transducer is located. In most cases, the waveform has the form of complex oscillations that contain deterministic and random components of the vibration process. Both the shape and the spectral composition depend on the measured vibration parameter. In practice, displacement, velocity, or acceleration is measured.

Vibration is characterized by the frequency f, i.e., the number of oscillations per second (Hz), amplitude A, i.e., wave offset, or the height of rise from the equilibrium position (mm), speed V (m/s) - the speed of the point or system under vibration, and acceleration - acceleration of the point or system under the action of vibration. The absolute values of the parameters that characterize the vibration vary widely, so use the concept of the level of parameters, which is the logarithmic ratio of the value of the parameter to its reference or threshold value.

This device is built using a piezoelectric transducer, which is known to be the most widely used for measuring vibration processes. They surpass all other types of vibration transducers in their technical characteristics because they have advantages: rather high sensitivity, wide frequency, and dynamic ranges of measurements, rather small sizes and weight, high heat resistance, and vibration resistance.

Piezoelectric vibration transducers (VTs) are VTs in which monocrystalline or polycrystalline materials having piezoelectric properties are used as a sensing element (Arnau., 2004) (Ebrahimi.,2011).

Piezoelectric transducers are active transducers that generate a measurement voltage without being energized by an external source. When assessing and predicting the technical state of various objects, piezoelectric accelerometers are used due to their ability to measure vibration in a wide frequency and amplitude range, small overall dimensions and weight, durability in operation, and ease of installation.

The action of piezoelectric VTs is based on the use of a direct piezoelectric effect (Arnau., 2004) (Ebrahimi.,2011), i.e. the properties of some materials to generate a charge under the action of mechanical force applied to them. The principle of construction of piezoelectric VT is shown in Figure 1.

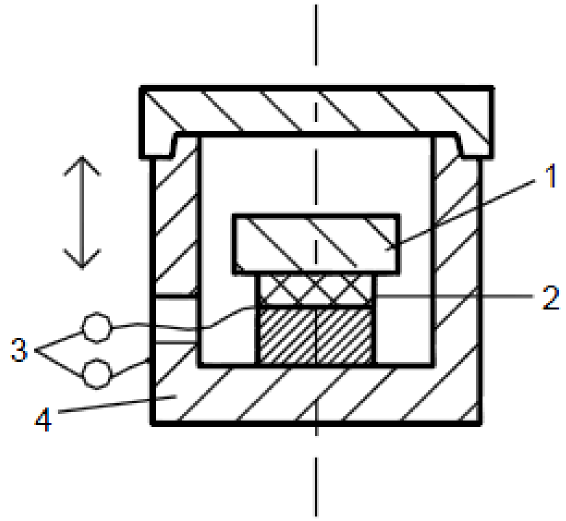

Fig. 1. Scheme of piezoelectric VT

The inertial element 1 is attached to the upper edge of the piezoelectric element 2, and the lower edge of the piezoelectric element is attached to housing 4. When installing the transducer on the object under study, the transducer receives the vibration information of the object. Due to the desire of the inertial element to maintain a state of rest, the piezoelectric element is deformed by the influence of the inertial force, where m is the mass of the inertial element and a is the acceleration of the object.

The deformation of the piezoelectric element and the electric charge that result is proportional to the acceleration. Therefore, these transducers are often called piezo accelerometers.

Poly- and single-crystal piezoelectric substances are used as a piezoelectric element.

The characteristics of the sensing element (SE) depend not only on the value of m but also on the stiffness K of the transducer, as well as on the presence of damping (i.e., the resistance to movement along with speed).

The force of elastic F_y acting on the inertial mass is known to be equal to

$$F_y = -kx, \quad (1)$$

where k is the stiffness coefficient, x -value mixing.

A characteristic feature of Vibro accelerometers is that they are considered systems with kinematic excitation. In such systems, the measured quantity acts not on the SE but on its base.

Let us introduce two coordinate systems: absolute X, located arbitrarily, and system Z, rigidly connected with the base of the vibration sensor. Then

$$F_y = -k\left(y-k\right),$$

$$F_d = -r\left[\frac{d\left(y-x\right)}{dt}\right],$$

$$F_{in} = m\left[\frac{d^2 y}{dt^2}\right]$$

where F_y is the elastic force, F_d is the damping force, F_{in} is the inertial force, r is the damping coefficient.

According to the d'Alembert principle

$$F_{in} = F_y + F_d$$

or

$$m\left[\frac{d^2 y}{dt^2}\right] = -k\left(y-x\right) - r\left[\frac{d\left(y-x\right)}{dt}\right], \qquad (2)$$

We transform equation (2) to the following form

$$\frac{md^2 z}{dt^2} + \frac{rdz}{dt} + kz = -\frac{md^2 x}{dt^2}, \qquad (3)$$

$$z = y - x$$

The quantity z is the mixing of the seismic mass relative to the sensor body, and x is the mixing of the sensor body relative to the absolute reference system.

Let vibration mixing x change according to a harmonic law, then

$$\frac{d^2}{dt^2} \to -\omega^2,$$

$$\frac{d}{dt} \to j\omega,$$

and

$$-\omega^2 z\left(t\right) + \left(r/m\right) j\omega z\left(t\right) = \omega^2 x\left(t\right),$$

where z(t) and x(t) are harmonic functions.

If the conditions are satisfied in the last equation $k/m << \omega^2; r/m << \omega$, then $z\left(t\right) \cong x\left(t\right)$. The latter means that the SE operates in the vibrometer mode, i.e., in a steady state, it monitors the amount of vibration mixing.

If $r/m >> \omega$ and $r/m >> k/m$, then $\left(r/m\right) z\left(t\right) \cong -j\omega x\left(t\right)$ and the SE also operates in the cycle meter mode, namely, the value $z\left(t\right)$ turns out to be proportional to the vibration velocity.

If $k/m >> \omega r/m$ and $k/m >> \omega^2$, then this is the operating mode of the vibration accelerometer.

Each of the considered modes can be implemented by choosing the appropriate characteristics of the SE: m, k, r and the range of operating frequencies. So for a vibrometer, it is important to ensure that the ratios are small k/m and r/m, since it operates in the resonant frequency range. For the velocimeter, it is necessary to use deep damping, and for the accelerometer, it is necessary to use a transducer with great stiffness. In the accelerometer mode, as follows from the above, $r << k/\omega$ for $\omega << \omega_0$, ω_0 is the natural frequency of the sensor.

2.2. Accelerometer operation

Since accelerometers are mainly used in vibrometry, we will analyze their work in more detail. To do this, replace the originals in equation (3) with their images:

$$z\left(t\right) = Z\left(p\right); x\left(t\right) = X\left(p\right), \qquad (4)$$

$$\frac{d}{dt} = p,$$

$$\frac{d^2}{dt^2} = p^2,$$

where p is the Laplace operator, and we introduce the following notation, $T = \sqrt{m/k}$ - period of the circular natural frequency of the sensor, $\eta = 2\xi T$ - damping coefficient. Then equation (4) can be represented as follows:

$$\left(T^2 p^2 + 2\xi Tp + 1\right) Z\left(p\right) = -p^2 X\left(p\right) T^2$$

or

$$W_1\left(p\right) = Z\left(p\right) / p^2 X\left(p\right) = T^2 / \left(T^2 p^2 + 2\xi Tp + 1\right).$$

This expression is the SE transfer function for acceleration, since

$$a\left(p\right) = p^2 X\left(p\right) = \frac{d^2 x\left(t\right)}{dt^2}.$$

The amplitude-frequency $A\left(\omega\right)$ and phase-frequency $\psi\left(\omega\right)$ characteristics can be obtained by replacing p with $j\omega$ in the SE transfer function and determining the modulus and argument of the complex frequency spectrum $W\left(j\omega\right)$, respectively:

$$A\left(\omega\right) = W\left(j\omega\right), \qquad (5)$$

$$\psi\left(\omega\right) = arctg\left[W\left(j\omega\right)\right]. \qquad (6)$$

After performing the indicated transformations, we obtain

$$A\left(\omega\right) = T^2 / \sqrt{\left(1 - T^2\omega^2\right)^2 + 4\xi^2 T^2 \omega^2}, \qquad (7)$$

$$\psi\left(\omega\right) = -arctg\left[2\xi T\omega / \left(1 - T^2\omega^2\right)\right]. \qquad (8)$$

If the admissible value of the dynamic error e is given, defined as

$$\delta_d = \left[A_1(\omega_h) - A_1(0)\right] / A_1(0),$$

then the cutoff frequency ω_h of the operating range is found from the condition

$$1 \Big/ \sqrt{\left[\left(1 - T^2\omega_h^{\ 2}\right) + 4\xi^2 T^2 \omega_h^{\ 2}\right]} - 1 = \delta_d .$$

The frequency ω_0, at which the resonance of the "sensitive element-transducer" system takes place, is called the resonant frequency and is determined by the formula

$$\omega_0 = \sqrt{\frac{k}{m}} . \qquad (9)$$

To expand the range of operating frequencies, it is necessary, as follows from (9), to reduce the seismic mass m or to increase the rigidity of its attachment. However, this also decreases the sensitivity of the sensor as a whole since it is proportional to T^2. Therefore, high-frequency sensors are less sensitive.

An important characteristic of the SE is also its transient impulse response, defined as the inverse Laplace transform of the function $W(p)$ (Li et al., 2016):

$$K(t) = \frac{1}{2\pi j} \int_{c-j\omega}^{c+j\omega} W(p) e^{pt} dp , \qquad (10)$$

where $K(t)$ is the impulse function, c - abscissa of absolute convergence.

In turn, $W(p)$ can be expressed in terms of the impulse transition function $K(t)$ by applying the direct Laplace transform to the latter:

$$W(p) = \int_0^{n\to\infty} K(t) e^{-pt} dt$$

Substituting the function $W(p)$, in formula (10) we obtain

$$K(t) = -\left[\frac{T}{\sqrt{\left(1-\xi^2\right)}}\right] e^{-\frac{\xi t}{T}} \sin\left[\left(\sqrt{\frac{1-\xi^2}{T}}\right) t\right]. \qquad (11)$$

It is known that the transient impulse function is the response of the system to the delta action of Dirac (Bahari et al., 2015), i.e., a pulse of infinitely short duration and infinitely large amplitude, the integral parameter of which is equal to one. If a non-periodic signal acts at the input of the system, then in the general case, the response function y (0 is determined by the Duhamel integral:

$$y(t) = \int_{n\to\infty}^{t} x(\tau) K(t-\tau) d\tau , \qquad (12)$$

where $x(\tau)$ is a function of the input action.

If $x(\tau)$ is a pulse signal of finite duration and amplitude, then at a short duration of this pulse in comparison with the period of the cyclic resonance frequency, the following formula is valid:

$$y(t) = S_0 K(t), \qquad (13)$$

$$S_0 = \int_0^{t_n} x(\tau) d\tau_i$$

where τ_i is the pulse duration.

The main advantages of piezoelectric VT are a wide range of operating frequencies, high vibration and shock strength, simplicity of design, low sensitivity to magnetic fields, the ability to create high-temperature transducers, the ability to create transducers with small size and weight.

The main disadvantages of piezoelectric VT are the presence of a large output resistance, dependence of the output signal on the cable length, the inability to measure the constant component of the dynamic process.

3. Results

The main goal of the project is to develop a system for monitoring vibroacoustic parameters of the working area.

The main functions of the system are: constant measurement of noise and vibration parameters of the working area, analysis of measured parameters, signalling of exceeding the allowed range of measuring parameters of the working area, display of measured data in decibels.

Based on the review and analysis of technical solutions, the main functions of the system were proposed a block diagram of the system, which is shown in Figure 2.

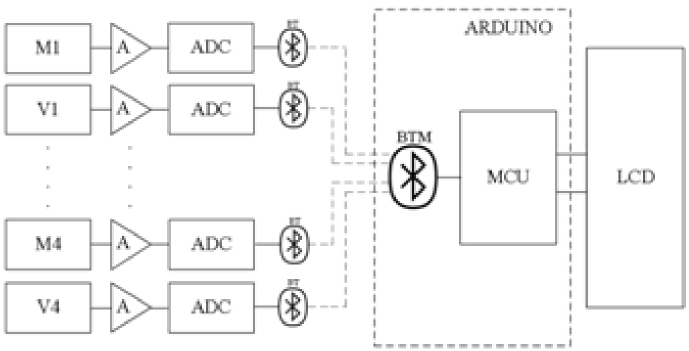

Fig. 2. Block diagram of the MVP system

The diagram shows:

- M1... M4 - microphones (noise sensors);

- V1… V4 - accelerometers (vibration sensors);

- A - amplifier;

- ADC - analog-digital converter;

- MCU - microcontroller;

- BTM - Bluetooth module for receiving a signal on the mainboard from measuring channels;

- BT - Bluetooth module connected to the sensor to transmit a signal to the mainboard;

- LCD - module for displaying the result.

Figure 1 shows that the system has 8 measuring channels - 4 for vibration measurement and 4 for noise measurement. Each measuring channel consists of the sensor itself (M1-M4 - microphone for noise measurement, V1-V4 - accelerometer for vibration). The data obtained from the sensors are amplified by the operational amplifier A, such amplifiers are 8, for each of the measuring channels. After amplification, the analog signal is converted into discrete code using a single-channel ADC. The digital signal after the ADC is transmitted to the mainboard with a microcontroller. The board receives data from all eight measuring channels. The results of collecting the values obtained from the sensors, the mainboard uses software processing to analyze the data and transmits them to the LCD display, which in turn displays them.

In the system, we propose to use the board "Arduino UNO" (Fig. 3). The main characteristics are shown in table 1.

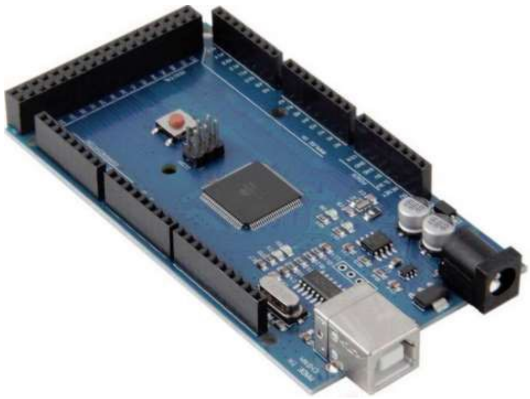

Fig. 3. General view of the ARDUINO UNO board

Table 1. Characteristics of the ARDUINO mainboard (Components101, 2021)

Microcontroller	ATmega 328
Supply voltage	7-12 V
Number of channels	8
Clock frequency	16 MHz
Operating voltage	5 V
Flash memory	32 KB
Digital inputs / outputs	14

As can be seen from Table 1, the ARDUINO board has eight input channels, which will allow us to process, analyze, and transmit data, and we, in turn, will use four channels for noise measurement and four channels for vibration. The use of multichannel during measurement will increase the accuracy of the obtained data. Since the board has a "Flash-memory," we will use it as a data warehouse for a given period, which will allow us to analyze the measured data for a given period of time.

A microphone is used as a sensor for each noise measurement channel. The analog signal from the microphone is amplified by an amplifier and converted into digital code by an ADC. Then the digital signal is transmitted to the mainboard with a microcontroller.

Noise parameters are measured by a sensor (microphone), and then the analog signal is fed to the amplifier. These two elements, the sensor and the amplifier, are located on the SFM board. Then the amplified analog signal is fed to a single-channel ADC (MCP3421), where it is converted into discrete code and can be amplified as needed 2, 4, or 8 times. The sampled signal is then sent to the Bluetooth module, then transmitted to the same Bluetooth module, but all connected to the ARDUINO mainboard.

Similarly, an accelerometer is used for each parameter measurement channel. On each measuring channel, both for vibration parameters and for noise parameters, the analog signal received from the sensor is amplified, sampled, and transmitted to the microcontroller.

Vibration parameters are measured by a three-axis accelerometer (sensor), and then the measured analog signal is amplified. As well as for measuring noise parameters, the sensor and amplifier are on the same board - SW420. The signal is then converted to digital code using the same ADC (MCP3421) and transmitted to the ARDUINO mainboard using the same Bluetooth module as for the noise settings.

There are eight measuring channels of vibroacoustic parameters, 4 of them for noise parameters and 4 for vibration parameters.

Digital signals from measuring channels by means of the Bluetooth module on each of the channels are transferred to payment through the same Bluetooth module.

On the board itself, the microcontroller contains a calibration characteristic used to analyze the received measurement signals, and then the processed data is displayed on the LCD display. Depending on whether the obtained values exceed the normal ranges of human work in such an environment, there may be an alarm about the excess.

In the system of monitoring of vibroacoustic parameters, data transfer from sensors to a processing board will be carried out by means of the Bluetooth module. A Bluetooth module will be connected to each measuring channel to transmit amplified and sampled data to the board. Such a module will also be connected to the board to receive a signal from the measuring channels.

The measuring channels of the designed system transmit the measured data via a wireless connection, which simplifies their use and placement in any place in the work area and allows to cover a larger area of the measured area. Analogs are portable devices that measure certain small planes of the working area.

As for the principles of operation, despite a large number of devices, the principle of their operation remains unchanged. The principle of measuring noise parameters is based on the received acoustic waves with the subsequent conversion of their energy by means of the most various technologies in electric potential, which is directly proportional to the size of a signal. As for the principle of measuring vibration parameters, vibration sensors are used, which perceive mechanical vibrations, which are also converted into the corresponding electric potential by means of various technologies.

The system of monitoring of vibroacoustic parameters performs the following functions:

- measurement of noise and vibration parameters;
- analysis of measured data;
- check for exceeding the allowed range of work;
- indication of measured data;
- alarm when exceeding the permitted operating range.

Since the measurement data coming from the sensors are not discretized, our system provides for the sampling of this data using an ADC. Calibration is performed for the normal display of the measured signal on the LCD display, so the previously found calibration characteristic will be entered on the ARDUINO mainboard. Also, as a system setting, it is possible to set the time of the sensor interrogation, i.e., with what interval the measured data from the measuring channels will be received on the mainboard.

As well as calibration characteristics, in the mainboard, namely in the microcontroller, the maximum values of ranges for parameters of noise and vibration for the analysis of the received measuring data will be entered.

After the analysis, depending on the result, an alarm will be performed to exceed the range, if any. The data will then be stored in the flash memory of the microcontroller. The last step is to display the measured data on the LCD display.

Therefore, taking into account all the functions of the system, the developed algorithm of the vibroacoustic parameters monitoring system is presented in Figure 4

Consider the developed algorithm of the system. As can be seen from Figure 4, after the initialization of the systems, calibration characteristics are entered to display the obtained sampled signal from the measurement channels in decibels.

Then, all measuring channels are connected to the mainboard and enter the survey frequency of these channels, namely the frequency of data acquisition.

After that, the connection of the measuring channels with the ARDUINO board is checked, if the connection is not stable, we return to the connection setting, but if it is stable, we start measuring the data.

The first stage of measurement is to check the set input frequency of interrogation of measuring channels. At the first initialization of the system, this stage is skipped because the mainboard has not yet received the measured data, so we immediately proceed to the survey of measurement channels. If the data during the survey of measuring channels is not received, then we return to the check of the set frequency. Upon successful survey of measuring channels and obtaining data, the analysis of these data is performed. The analysis is followed by a comparison with the maximum allowable values for workplace work for noise and vibration parameters. If the data exceeds, then the signal is exceeded, and after entering the received data in the flash memory of the microcontroller, if the data does not exceed the maximum allowable values, the data is saved.

4. Conclusions

Solving the problem of identifying aircraft defects using the changes in the dynamic characteristics of the controlled objects caused by them, the article proposed a system for monitoring the vibroacoustic parameters of the working area, which performs the following functions: measurement of vibroacoustic parameters (vibration and noise parameters) of the working zone; analysis of measured values of vibroacoustic parameters; alarm of the user about exceeding of the allowed range of parameters of vibration and noise of a working zone; saving the measured data for a specified period of time; display of measured data.

The use of the developed system for monitoring vibroacoustic parameters will allow detecting such types of defects as a violation of the integrity of structures, loosening of fasteners and the appearance of gaps in the joints of units, backlash in mechanical systems for transferring forces or displacements, increased dry friction in the supports of deflected surfaces, resonant modes of vibration of elements and systems airframe, insufficient efficiency of hydraulic dampers in the elastic airframe.

The developed system has a number of advantages due to the selected technical solutions, namely a sensor for measuring vibroacoustic parameters, which meets the needs of the task and has the following advantages: large measurement range, low noise, signal frequency range, signal-noise ratio. The use of ADC in the system allows the selection of the sampling frequency of the signal programmatically. Also, the advantage of the system is the use of a Bluetooth module, which has a long-range of signal reception, which will allow us to place measuring channels in any desired place in the work area, and the board has a high level of data protection. The measuring channels of the developed system transmit the measured data by means of a wireless connection, which simplifies their use and placement in any place of the object of control and allows covering a larger area of the measured area.

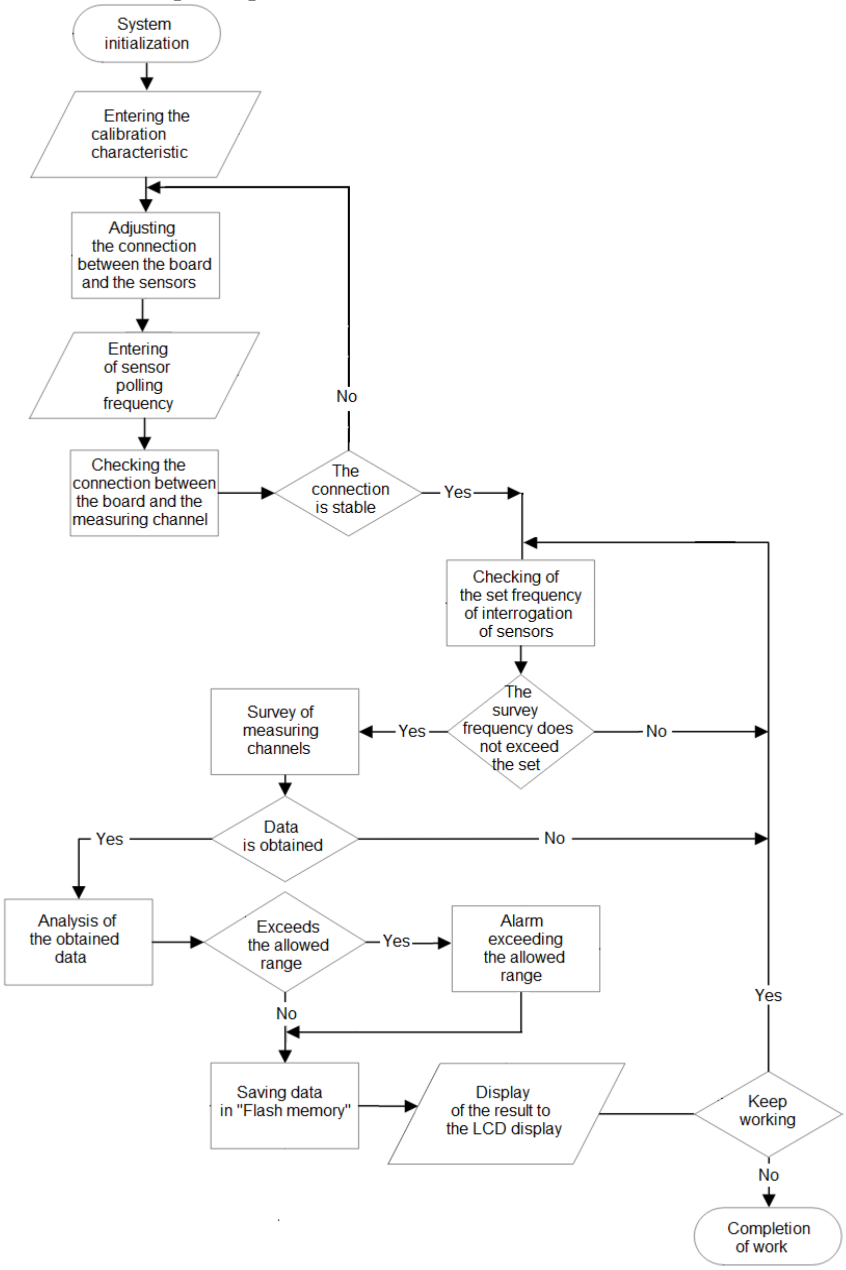

Fig. 4. Algorithm of measurement system operation

Abbreviations

VTs	vibration transducers
MCU	microcontroller
A	amplifier
M	microphones
V	accelerometers
LCD	module for displaying the result
ADC	analog-to-digital converter
SFM	SparkFunMicrophone
BTM	Bluetooth module for receiving a signal on the mainboard from measuring channels
BT	Bluetooth module connected to the sensor to transmit a signal to the mainboard

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Review Article

Aerospace Industry and Aluminum Metal Matrix Composites

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Abstract

Researchers have turned to search for new materials that will meet all the aerospace industry requirements. When it is almost impossible to achieve this with a single material, composite materials have been studied, and there have been great developments in this field. Many elements are used in aircraft construction, but aluminum is the most preferred due to its low density, good castability, high strength, corrosion resistance, and good fatigue strength. However, its strength and stiffness limit its usability. To solve this problem, aluminum is combined with various elements. Aluminum metal matrix composites are an example of this. Aluminum metal matrix composites are preferred in aircraft applications due to their high specific modulus and good mechanical and thermal properties. This review provides information on the use of aluminum metal matrix composite materials in the aerospace industry.

Keywords

Aluminum metal matrix composites
Aerospace industry
Mechanical properties
Aluminum

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1. Introduction

The search for new and advanced materials will continue, with modern technological developments and consumers' demands for lighter, energy-efficient, stronger, and cost-effective systems and machines. The properties of the materials used in aerospace are constantly improved in line with technological developments to meet safety and operational standards.

Aluminum-based metal matrix composites can be used in many industries. In recent years, the use of aluminum matrix composites in aviation has become widespread. Materials in aircraft must be lightweight and able to withstand high temperatures for extended periods in harsh environments. Aluminum composites are the preferred choice for aircraft fuselage, wing, and support structures. The fuselage of an airplane consists of approximately 80% aluminum by weight. Offering lower production costs, the ability to create complex shapes, and the inclusion of innovative design concepts, aluminum die casting technology is gaining importance. Aluminum metal matrix composites are preferred because of their lower density, excellent specific strength and hardness, high modulus, good thermal properties, better wear, and corrosion resistance (Nturanabo et al., 2019). Aluminum metal matrix composites are attractive materials for thermal management and have a high volume reinforcement fraction (Raju et al., 2016). It is possible to further improve the thermal conductivity of the composite material by using high thermal conductivity reinforcements. In the metal matrix composites, aluminum and copper were often used as matrices due to their high thermal conductivity. Their reinforcements consisted of carbon, SiC, and diamond. There is a growing interest in using Metal matrix composites in the aircraft industry (Akhil, 2018). Because of their great

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potential for the production of lightweight, structurally efficient aircraft components, these materials are usually selected for their lightweight and ability to withstand the stresses generated during operation, aluminum metal matrix composites have been used in these studies (Kolia et al., 2015) (Kaushik et al., 2015).

This article evaluates increasing efforts to exploit the potential of these materials in the aerospace industry. There are some studies about the new types of these aluminum composite materials currently in research. The studies about aluminum-based composites can improve their use in aircraft applications. Their properties were reviewed, and the results were introduced as reinforcement contents increased in the matrix material, the hardness of the composites also increased with an increase in tensile strength and decrease in elongation. Studies on this subject can provide better properties in aluminum matrix composites for aircraft applications. This study introduces the use of aluminum metal matrix composite materials in the aircraft industry. It will give general information about these materials, their different applications, and their advantages and disadvantages. Aluminum-based metal matrix composites can be used with their desired properties for specific

2. Material Selection in Aerospace Industry

Material selection is one of the most important functions of effective engineering design as it determines the industrial and economic reliability of the design. A great design may not be a profitable product if it cannot find optimal material combinations. So it is vital to know what the best materials for a particular design are. For this reason, engineers use several facts of materials to arrive at the most reasonable decision. They are mainly concentrated on the properties of the materials, which are identified as the potential materials for that specific design.

Material selection is a conflicting decision-making process. Because mostly, lightweight materials may not have sufficient strength, and brittle materials will not be suitable for fatigue resistance, stiffness, or toughness. Moreover, it is almost impossible to find one single material that provides all desired properties for engineering applications. Additionally, material properties are strongly affected by the working environment, such as temperature, pressure, humidity, and the nature of loading such as gradual, fluctuating, impact, fatigue. Accordingly, there is a need to combine two or more materials as alloys or composites so can take advantage of the different useful properties offered by combining different materials. In the aircraft industry, aluminum alloys/composites overtake other metals, especially due to their mechanical stability, thermal management, and lightness (Nturanabo et al., 2019).

There are some metal matrix composites types such as nickel, aluminum, refractory, and etc. Fillers in the metal matrix composites are silicon carbide, aluminum oxide, titanium carbide, and other fillers. The industries which use the metal matrix composites are aerospace and defense, automotive and locomotive, electrical and electronics, industrial, and other end-user industries (Metal Matrix Composites Market - Growth, Trends, COVID-19 Impact, and Forecasts, 2021).

Aluminum matrix composites have been used in many different sectors, such as the aerospace industry, automobile production, or power electronics. Aluminum matrix composites produced by equal channel angular extrusion have very high strength. This is due to a very fine-grained structure. However, they are very temperature-sensitive. An adapted joining technique is required. In this respect, soldering offers some advantages compared to other joining processes such as welding or bonding. Sn-based filler metals are suitable for this purpose due to their low melting range below 300 °C; Ag and Cu are common alloying elements. Disadvantageous features are low strength and creep resistance of the joints. The improvement of these properties can be achieved by the development of Sn-based composite fillers by adding ceramic reinforcement particles such as Al_2O_3 or SiC. Investigations were made towards the formation of an interfacial reaction layer between the reinforcement particles and the filler matrix. Ti was alloyed as the active element to improve the bond between the matrix and the particles. In such studies, the microstructure observed by SEM can be evaluated by associating it with the results of the tensile tests (Wielage et al., 2010).

The chemical composition of Al alloys affects their electrochemical potential and the distribution of the various phases in the microstructure, as well as the corrosion behavior. Corrosion forms depending on the structure, e.g., intergranular attack, exfoliation, and stress corrosion cracking (SCC) were encountered with heat treatable, high strength alloys, preventing exploitation of maximum potential strength of wrought products. Corrosion resistance was improved with new metallurgical processes and compositional modifications. Exfoliation corrosion and SCC behavior can be significantly improved for copper-bearing 7XXX series alloys by duplex aging; however, strength is compromised. In recent years an optimum combination of strength and corrosion characteristics was provided by the development of optimized heat treatment procedures (Peters and Leyens, 2009).

3. Metal Matrix Composites

Metal matrix composites are modern and well-developed lightweight materials composed of an element or an alloy matrix. This matrix consists of two-phase; the second is fixed into the surface and then distributed to provide some developments. Depending on the size, shape, and amount of the second phase, the composite property varies. Composite has excellent benefits due to the combined metallic and ceramic properties, and accordingly, it provides improved physical and mechanical properties. It represents a new generation of engineering materials in which strong ceramic recruitment is integrated into a metal matrix to improve its properties as a specific strength, specific stiffness, wear resistance, corrosion resistance, and elastic modulus. Whereby composites, the metallic properties of matrix alloys such as ductility and toughness are combined with the ceramic properties of reinforcements such as high strength and high modulus, thus providing greater strength in shear and compression and higher service temperature capabilities. These properties help to understand the scientific, technological, and commercial importance of composites (Vijayaram and Baskaralal, 2016).

Metal matrix composites are composed of a metallic matrix and a dispersed phase which a second phase or phases have been artificially introduced. This is in adverse to conventional alloys whose microstructures are produced by phase transformations that occur naturally during processing. Metal matrix composites are differentiated from the resin matrix composites with their metallic nature and being appropriate to conventional metallurgical processing operations. Metal matrix composites more comprehensively improved resin matrix composites by the preference of their metallic nature. This can be explained by their physical and mechanical properties and by their ability to lend themselves to conventional metallurgical processing operations. Some of the properties that differentiate metal matrix composites from resin matrix composites can be indicated as electrical conductivity, thermal conductivity, and non-inflammability, matrix shear strength, ductility and abrasion resistance, ability to be coated, joined, formed and heat treated. These composites have been developed for weight-critical applications in the aerospace industry, and they are a class of advanced materials. Composites reinforced with isotropic properties can be formed in a three-dimensional or planar region. This shows that they are suitable to be developed for requirements (Vijayaram and Baskaralal, 2016).

Table 1 shows the typical reinforcement used in metal matrix composites. Metal matrix composites can be defined as the materials with microstructures that involve a continuous metallic phase into a second phase, or phases, have been artificially introduced. This is in contrast to the situation where the microstructures of conventional alloys are produced by phase transformations during processing.

Table 1. Typical types of reinforcements used in metal–matrix composites (Chawla, 2012) (Akhil, 2018)

Type	Aspect ratio	Diameter	Examples
Particle	1–4	1–25 μm	SiC, Al_2O_3, BN, WC
Short fiber (whisker)	10–10000	1–5 μm	C, SiC, Al_2O_3, SiO_2 + Al_2O_3
Continuous fiber	> 1000	3–150 μm	SiC, Al_2O_3, C, B, W, Nb + Ti, Nb_3Sn
Nanoparticle	1–4	< 100 nm	C, Al_2O_3, SiC
Nanotube	> 1000	< 100 nm	C

Table 2 gives applications of metal matrix composites in the aircraft industry and space applications as an overview.

Much of the research in the aircraft industry is to develop the thrust-to-weight ratio of their engines. This can be done either by enhancing thrust or by decreasing the weight. They stress the materials and also increase the working temperature, which affects the entire range of engine parts, e.g., blades, shrouds, and discs. Metal matrix composites can be used in the aircraft industry and space applications. Titanium-matrix composites with silicon carbide or boron reinforcement display good characteristics at room temperature and elevated temperatures. This makes it a good material for fan blade applications at elevated temperatures. One recent improvement was in the precipitation-hardenable aluminum alloys, Al-Li alloys. When Li is alloyed to AI, it decreases the density and increases the elastic modulus of the alloy.

4. Aluminum Metal Matrix Composites

The aluminum alloys have low density, good corrosion resistance, capability to be strengthened by precipitation, high vibration damping capacity, and high thermal and electrical conductivity. Due to these properties, aluminum alloys are very favorable for metal matrix composites. Aluminum matrix composites have been used since the 1920s. They can be used in a large area due to a variety of mechanical properties because of the chemical composition of the aluminum matrix. Some of the applications of Al MMCs are shown in Figure 1 and Figure 2.

They are usually reinforced by aluminum oxide, silicon dioxide, silicon carbide, carbon, boron nitride, graphite, boron, boron carbide, etc. And aluminum nitride is also dispersed in the matrix (Sayuti et al., 2016). In the transportation industries, discontinuously reinforced aluminum matrix composites began to be developed in the 1980s. Their isotropic mechanical properties make them very attractive, and additionally, the costs are lower.

Table 2. An overview of various applications of metal matrix composites in the aircraft industry and space applications (Akhil, 2018).

	Components	Property requirement	Currently Using MMC	Literature
Aircraft	Engines	Improved high-temperature strength, creep resistance, stiffness.	Nextel/Al, Cu-Nb, Cu-Nb3Sn	(Haghenas, 2016) (Mavhungu et al., 2016)
	Airframe	Improved strength and stiffness	B/Al	(Rawal, 2001)
Space	Satellites	Lower (zero) CIE, higher stiffness,	B/Al	(Rawal, 2001)
	SDI	Higher thermal conductivity with high temperature strength.	Gr/Al	(Rawal, 2001) (Badiey and Abedian, 2010)
	Space panels	Higher-strength at temperature and low density.	Gr/Al, SiCp /Al	(Rawal, 2001)

Fig. 1. Applications of Al MMCs
(a) Piston,
(b) engine with cylinder barrel,
(c) piston connecting rod,
(d) brake system made of aluminum
(Al) metal matrix composites (MMCs). {2019} {Vikas Verma and Alexandra Khvan}. Originally published in {IntechOpen Book Series} under {Creative Commons Attribution 3.0 Unported (CC BY 3.0)} license. Available from: {10.5772/intechopen.83584},

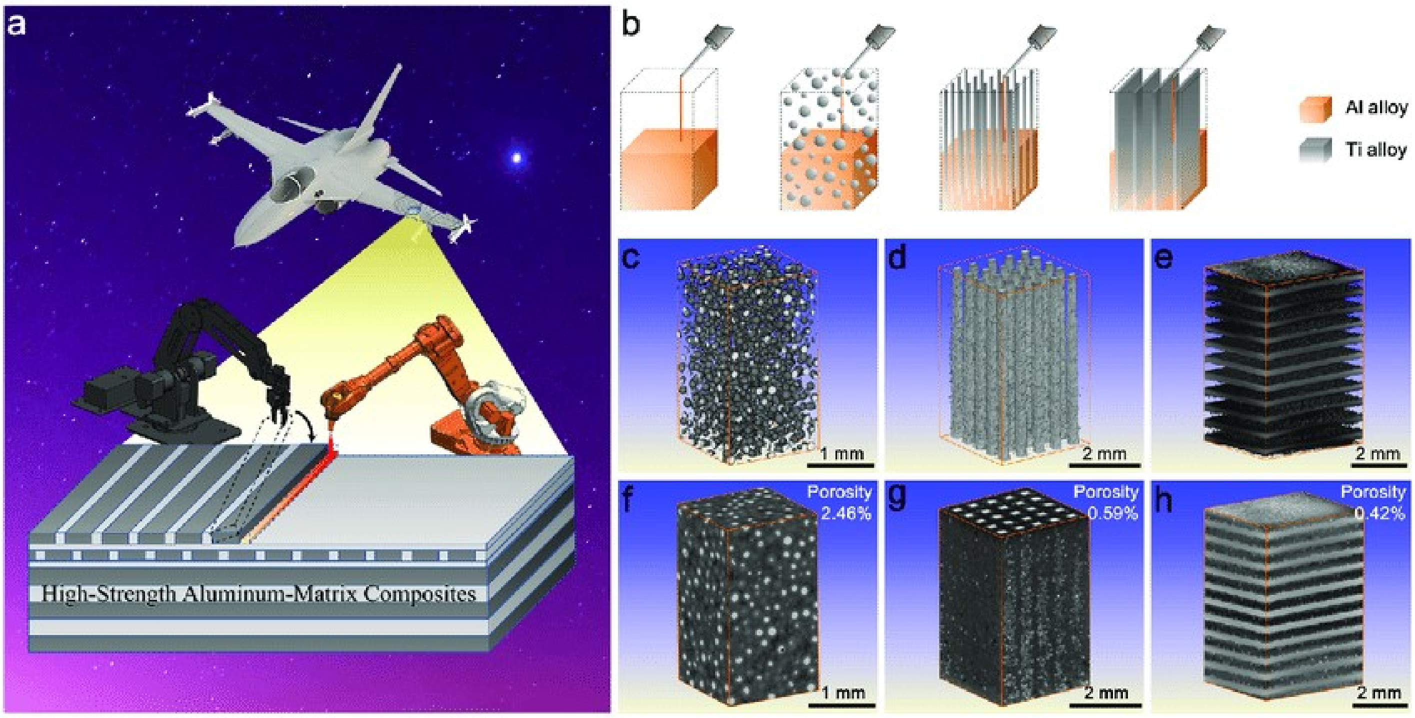

Fig. 2. Application and fabrication of high-strength aluminum–matrix composites (AMCs).
(a) Schematic illustration of high-strength AMCs potentially applied in the aerospace industry.
(b) Illustration of typical Al–Ti composites fabricated by a microcasting process.
(c–e) Perspective view of the Ti–6Al–4V skeletons in actual AMCs imaged by high-resolution X-ray tomography:
(c) ball-reinforced AMC,
(d) rod-reinforced AMC, and
(e) plate-reinforced AMC.
(f–h) Corresponding overall morphology for the three reinforced AMCs. {2019} {Shao, C., Zhao, S., Wang, X., Wang X., Zhu Y., Zhang Z., and Ritchie R. O.} Originally published in {NPG Asia Mater 11} under {Creative Commons Attribution 4.0 International License} license. Available from: {10.1038/s41427-019-0174-2}

The properties of composites of MMCs are like a compromise between matrix properties and reinforcement phases properties. The composition and properties of the matrix phase affect the properties of the composite both directly and indirectly. It can be explained as normal strengthening mechanisms in a direct way, and chemical interactions at the reinforcement/matrix interface are indirect way. Aluminum-based composites which are reinforced with ceramic particles offer some improvements over the matrix alloy. These are higher elastic modulus than of 70GPa, thermal expansion coefficient which is closer to that of steel or of cast iron, greater and improved resistance against thermal fatigue and rupture stress. Additionally to these benefits, observed that decreases in elongation to failure and fracture toughness.

Increasing the weight fraction percentage of silicon carbide particulates addition in the LM6 alloy matrix has increased ultimate tensile stresses, modulus, yield but a reduced strain to fracture (Chawla and Shen, 2001) (Sayuti et al., 2016). Therewithal, it appears that the silicon content of the matrix has a more dominant effect in reducing the fracture sequence than the increase in silicon carbide particle addition (Sayuti et al., 2016).

Primary compositing processes of aluminum metal matrix composites for industrial-scale manufacturing can be divided into two main groups as liquid-state processes and solid-state processes. Liquid state processes are classified as a liquid metal mixing processes and liquid metal infiltration processes. Liquid-metal mixing is the primary means of compositing the production of materials intended for solid-state processing for high volume automotive applications, high volume electronic packaging applications, liquid-metal infiltration, and high-performance aerospace applications (Nturanabo et al., 2019).

Considering the ease of production and the final quality of the desired composite, the processing methods of aluminum matrix composites are constantly changing. The best-known processing techniques of aluminum matrix composites are stir casting, powder metallurgy, spark plasma sintering, squeeze casting, friction stir processing, liquid metal infiltration, spray code position, and reactive in situ techniques have elaborated here with their respective distinguishing features and mechanical properties of the fabricated composites. The type of processing method, the processing parameters, and the type, size, and composition of the reinforcement material affect the mechanical properties of aluminum matrix composites. Relatedly, the mechanical properties of aluminum and its alloys are greatly improved by adding various reinforcing materials with a wider spectrum (Aynalem, 2020).

Reinforced graphite fibers with aluminum and magnesium matrices are utilized in satellites, missiles, and helicopter structures in order to make storage-battery plates, lead matrix composites having graphite fibers are used. Graphite fibers embedded in the copper matrix are used to produce electrical contacts and bearings. Boron fibers in aluminum are harnessed as structural supports and compressor blades. The same fibers in magnesium are used in the construction of antenna structures. Titanium-boron fiber composites are used in jet engine fan blades (Meetham, 1989) (Vijayaram and Baskaralal, 2016). In order to make high-temperature engine components, molybdenum and tungsten fibers are dispersed in cobalt-base superalloy matrices. Squeeze cast MMCs have much better reinforcement distribution compared to composite cast materials generally. The reason for this is the use of a ceramic preform that contains the desired weight fraction of reinforcement rigidly attached to one another so that movement is inhibited (Rizkalla and Abdulwahed, 1996) (Vijayaram and Baskaralal, 2016). As a result, clumping and dendritic segregation are eliminated. Since pressure is used to force the metal into interfiber channels, displacing the gases Porosity is also minimized. Because of heat flow patterns, grain size and shape can vary along the infiltrated preform. Since the lower freezing solute-rich regions diffuse toward the fiber ahead of the solidifying matrix, secondary phases typically form at the fiber-matrix interface. Recently, the automotive, aerospace, and military industries have been promoting composite materials technological development to achieve good stiffness/density ratio and mechanical strength/density. Particulate reinforced metal matrix or modern fiber-reinforced composites are produced by casting techniques. Table 3 shows the industrial applications of these metal matrix composites and their special futures (Polmear, 1981) (Vijayaram and Baskaralal, 2016). High longitudinal and transverse strengths at various temperatures, near-zero coefficients of thermal expansion, good electrical and thermal conductivities, and perfect antifriction, anti-abrasion, damping, and machinability are some of the properties (Vijayaram and Baskaralal, 2016).

The application of composite materials has come to a good position in aircraft technology over time. It is now applied in fuselage-production technologies as well as in jet engine development. Although not as common as in aircraft technology, application in car technology is also growing very rapidly (Patridge, 1989) (Vijayaram and Baskaralal, 2016). Its applications in the electronics industries are also growing significantly. The main reasons for this are its mechanical, electrical, and heat resistant properties. Compared to traditional materials used in laser and computer parts, composite material parts applied in electronic sub-assemblies create a more efficient working environment and are durable at higher temperatures (Vijayaram and Baskaralal, 2016).

Aluminum alloys and composites have played a major role in the development of aircraft and rocket technology. Aluminum created and developed humanity's potential to fly around Earth and into space. It would not be wrong to say that the Wright brothers pioneered this because they used aluminum in the engines of their first biplane. And it is known that NASA used an aluminum-lithium alloy in its spacecraft (Nturanabo et al., 2019).

Aluminum alloys and/or composites are preferred for the fuselage, wing, and support structures in commercial and military aircraft or cargo aircraft. Aluminum makes up 80% of the weight of the fuselage of a typical modern commercial transport aircraft. Today, the focus is on aluminum casting technology, which offers lower production costs, the ability to create complex shapes, and the flexibility to combine innovative design concepts (Nturanabo et al., 2019).

Since the launch of Sputnik 1 on 4 October 1957, aluminum metal matrix composites have been the material of choice for space structures of all kinds. Aluminum metal matrix composites and alloys were selected for their ability to withstand the stresses occurring during launch and operation in space. Their lightweight specification was used in the Apollo spacecraft, Skylab, space shuttles, and the International Space Station. Aluminum alloys/composites overtake other metals, especially due to their mechanical stability, thermal management, and lightness (Nturanabo et al., 2019).

Metal matrix composites are candidates for use in aerospace industries because of their high elastic modulus, strength, and low density. The requirements for improved performance and higher trust-to-weight ratio in aerospace industry applications have resulted in the use of Ti which has high strength and density. The fatigue strength of composites is advantageous. Another advantage is the ability to adjust the orientation of fibers to the principal axis of stress. This allows designing the material for the application. Problems with the application of metal matrix composites include a lack of experience and confidence as well as current costs. These include costly fabrication techniques that can be used in the manufacture and in the field repair or overhaul provisions and specific application problems such as foreign object damage and erosion in engine fan components. Fabricating Be/Ti calls for the hygienic precautions needed for using Be in any form. The additional ventilation sampling and health check add to the cost. An emotional reaction to the use of Be must always be coped with (NMAB ad hoc Committee on Metal-matrix composites, 1974).

5. Commonly Used Aluminum Alloys in The Aerospace Industry

The most common aluminum alloys used for aerospace applications are AA 2014, AA 2024, AA 5052, AA 6061, AA 7050, AA 7068, AA 7075. The less common aluminum alloys used for aerospace applications are AA 2219, AA 6063, AA 7475 (Danylenko, 2018). The Wright brothers used aluminum for their first manned flight in 1903. This is also the first use of an aluminum alloy by heat strengthening. With this use, the preference for aluminum in aerospace engineering has increased. In recent years, materials with different properties have been needed in the aviation industry. It has been determined that extremely durable and fatigue-resistant materials are needed in aviation. Thus, the development and use of various types of aluminum alloys have been achieved. Table 4 gives the typical mechanical properties of some commonly used aerospace aluminum alloys.

Table 3. Characteristic features and applications of metal matrix composites (Polmear, 1981) (Vijayaram and Baskaralal, 2016).

Metal Matrix Composite Type	Industrial Application	Special Features
Graphite reinforced in Aluminum	Bearings	Cheaper, lighter, self-lubricating, conserves Copper, Lead, Tin, Zinc
Graphite reinforced in Aluminum, Silicon Carbide reinforced in Aluminum, Aluminum Oxide reinforced in Aluminum	Automobile pistons, cylinders liners, piston rings, connecting rods	Reduced wear, anti-seizing, cold start, lighter, conserves fuel, improved efficiency
Graphite reinforced in Copper	Sliding electrical contacts	Excellent conductivity and anti-seizing properties
Silicon Carbide reinforced in Aluminum	Turbocharger impellers	High temperature use
Glass or Carbon bubbles reinforced in Aluminum		Ultra-light material
Cast Carbon fiber reinforced Magnesium fiber composites	Tubular composites for space structures	Zero thermal expansion, high temperature strength, good specific strength, and specific stiffness
Zircon reinforced in Aluminum-Silicon alloy, Aluminum Silicate reinforced in Aluminum	Cutting tool, machine shrouds, impellers	Hard, abrasion-resistant material

Table 4. Typical mechanical properties of some commonly used aerospace aluminum alloys (Prasad and Wanhill, 2017)

Alloy	Temper	Density (g/cm³)	Elastic Modulus (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Fracture Toughness (MPa√m)
2014	T6	2.80	72.4	415	485	26.4
2219	T62	2.84	73.8	290	415	36.3
2024	T4	2.77	72.4	325	470	22.0
7050	T74	2.83	70.3	450	510	38.5
7075	T6	2.80	71.0	505	570	28.6

6. The Future of Aluminum Alloys in Aircraft Technology

The future of aluminum alloys in aircraft technology looks bright. The demand for aluminum is expected to increase in the coming years. Therefore, there is increasing interest in recycled alloys to meet the ever-increasing demands in the aerospace industry. In addition, many studies are carried out to improve the materials used. For example, aluminum-lithium alloys were developed for the aerospace industry by reducing the weight of airplanes and then increasing the performance of airplanes. These alloys have high specific modulus, excellent fatigue, low density, and cryogenic toughness properties. They are advanced materials by these properties. In the coming years, there will be more innovations in aluminum alloys in increasing studies.

Scientists have created superior materials by metals with other alloys, ceramics, and other organic compounds in order to improve the properties of standard materials. E.g., aluminum can be reinforced with boron, carbon, silicon carbide, alumina, or graphite to create a composite that is 30% to 40% stronger and more rigid than barebones aluminum. Metal matrix composites break down into four different categories; dispersion hardened and particles, layer composites, fiber composites, and infiltration composites. Some of the advantages of using metal matrix composites are; higher temperature capability, fire resistance, higher transverse stiffness, and strength, no moisture absorption, higher electrical and thermal conductivities, better radiation resistance. The design required to make products lighter but still maintain their productivity has increased the demand for metal matrix composites. These materials are being used in a variety of industries, including automotive and aerospace applications. Manufacturers then utilize these composites to create better, more stable, and lighter-weight products for various industries (i.e., automotive, aerospace, and defense). The need for lightweight and high tensile strength parts are the driving factor for the demand for aluminum to soar. Aluminum will continue to grow and be the leader of metal matrix composites. Refractory matrix metals, metals that contain ceramic material, are poised to be the second-largest metal matrix composites market. Their demand will grow due to its multifunctional properties. They can be used for tools, nuclear radiation control rods, solar panels, spacecraft exteriors, and catalysts in chemical reactions. They have high tensile strength, malleability, and ductility. It looks like the future is here. Metal matrix composites are going to change industrial fabrication for years to come. That being said, researchers admit that they have only just begun to explore the possibilities of these new materials. However, the use of custom-designed metal matrix composites will continue to expand into an enormous number of applications (Barret, 2017).

7. Results and Discussion

In recent years, a lot of research has been done and improved on materials in the aircraft industry. The materials must be lightweight and be able to withstand hard conditions. Aluminum alloys and composites are very important in the development of aircraft and rocket technology. Aluminum alloys and composites give better results than other metals in some areas, e.g., mechanical stability, damping, thermal management, and reduced weight. Aluminum metal matrix composites are appropriate materials for thermal management as they have a high volume reinforcement ratio. Aluminum's lightness, transportation costs, and volume are superior to other materials.

Aluminum metal matrix composites are considered as potential material candidates for a wide variety of structural applications in the transportation, automobile, and sports goods manufacturing industries due to the superior range of mechanical properties they have. The primary benefit of these composites is the adaptability of their mechanical and physical properties to meet specific design criteria.

8. Conclusions

Due to their properties, aluminum metal matrix composites are suitable for different special applications and are also used in the aircraft industry. Research and developments can increase the use of aluminum metal matrix composites in the aircraft industry. Aluminum metal matrix materials have some advantages, such as low cost and ease of processing. They are preferred because of their high specific modulus, good mechanical and thermal properties for aircraft applications. The development of aluminum matrix composites is very important in meeting the requirements in various industries. These composite materials are constantly replacing traditional engineering materials due to their properties, such as low density, better corrosion resistance, high abrasion and wear resistance, high thermal conductivity, high specific modulus.

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Research Article

Ergonomic Risk Factors in Ground Handling Operations to Improve Corporate Performance

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Abstract

Ground handling operations can be accepted as the heart of safe flight, beginning from the ground to the air. In ground handling activities where there is tight time pressure, human resources are of great importance in efficient and safe service. This study presents ergonomic risk factors affecting the operational and corporate performance of aircraft ground handling services. Ergonomic related performance fields are identified via expert opinion and a taxonomy focusing on classified error conditions for ground handling services. The taxonomy is developed to improve corporate performance while eliminating ergonomic risks and maintaining a safe working environment. Identified performance risks are intended to be a guide for operational managers in aircraft ground operations in the field of investments, decision making and safe operations.

Keywords

Ergonomic risk
Human factors
Ground handling
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1. Introduction

The aviation industry defines hazard identification and safety risk management as core processes involved in the management of safety. The concept of safety in aviation may have different connotations, like freedom from hazards or no accident. So, it is essential to understand and identify the factors that cause or are likely to cause harm (Čokorilo and Dell'Acqua, 2013).

Ideas on the impact of the human factor in aviation have inspired the scientific world. Many types of research are carried out and developed models to explain the existence of a relationship between the human factor and the risk of a health or life-threatening event. The risk associated with the presence of the human factor is particularly striking in aviation. There are some uncertainties in aviation operations which make up the risk definition. Those uncertainties are associated with the threat of losing some of the values like life, health, material goods. Otherwise, the perception of risk is influenced by personality factors and situational factors (Uchroński, 2020).

Ground handling operations are one of the most important work performances in the civil aviation flight cycle. Ground handling refers to the wide variety of activities for the flight operations, such as passenger services, flight operations, catering, and baggage handling (EC, 2021). In handling aircraft while refueling, cleaning, loading/unloading, towing, and so forth,

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effective and safe performance needs to be achieved. The ramp area is also risky both for personnel and operations. Improper use of ground handling equipment, careless and untrained staff may increase safety concerns (Ek and Akselsson, 2007).

As the aviation industry has grown rapidly, supportive handling operational activities need to be grown as well. An increase in traffic means the number of accidents and adverse impacts may rise even in the safest system (Luxhøj et al. 2001). For the efficiency and sustainability of airlines, airport apron area operations are significant. The operation time in this area is short, and at the same time, several activities with different equipment have to be implemented. For that reason, there is a high potential risk for accidents and incidents (Sari et al., 2015). The methodology in this study was determined as taxonomy. Taxonomy is a process approach to deal with risks as to the initial step of the whole management system. In this view, we have tried to embody all related ergonomic factors in a taxonomy. Taxonomy has been designed under four main groups in the view of sustainability management for identified fields that may have an impact. This taxonomy may consider a holistic picture of organization-wide risk factors by managers to reach corporate performance. In this taxonomy for aircraft ground operations, we have identified 13 risks obtained from literature and experts' opinions in the aviation sector.

Corporate performance is a compound evaluation of an organization in, typically, financial, market and shareholder performance parameters. Corporate performance analysis is concerned with the health of the organization. Traditionally, financial performance was significant. Today, the concept has become broader and corporate performance management (CPM) focuses not only on forecasting, budgeting and planning and performance results but also in non-financial areas monitored for corporate performance management and reporting, including strategic planning, process efficiencies, brand equity, risk management and human resource management (HRM) (Wigmore, 2015). Guest et al. (2003) explore the relationship between the use of human resource management and a range of performance measures in manufacturing and service organizations. Kansoy and Bakanoğlu (2021) stated that aviation-related intense workload, staff performance stress may cause accidents and incidents as well as the impact of the nature of human. Bastola (2017) developed a rewarding universal performance model for corporate aviation performance focusing on the employee, teamwork, leadership so on.

Human makes mistakes naturally, so the variable qualities of human resources create difficulties in managing their corporate performance. This is exactly why the sources of error must be identified and managed in a way that does not cause errors. The physical and mental workload affects the health and performance of the ground operations personnel. The level of total workload is significantly affected by environmental and organizational factors as well as mental and physical factors (Emeç and Akkaya,2018; Can and Delice, 2020). If individual performance increases and is used for achieving corporate aims, corporate performance will also increase in view of ground handling services.

Ground handling operations also enable the formation and development of collaborations with aviation sector stakeholders. Managers also will be able to see to which areas they will allocate resources with this taxonomy. This taxonomy may contribute to proactive monitoring of the risk sources about human factors. The proactive approach is important to saving sources. Also, this proactive approach will be useful in reducing the negative effects of risks arising from risk sources before accidents and breakdowns occur.

This new taxonomy, designed as a decision-making tool, may be used as a guide to managing risk for improving both operational and corporate performance. Then managers can also use this taxonomy to manage risks in ground operations. This tool may support in achieving their managerial decision skills for developing human resource qualifications, scheduling workload, mental and physical conditions.

To improve corporate performance on ground operations, many efforts are needed to assure safe operational conditions preventing from hurting the personnel (Sari, 2015). Identifying the ergonomic risk factors aims to evaluate the risks and try to control those activities in the phase of aircraft preparation and turnaround at the ramp area.

Ground handling operations employees are the first to intervene on the aircraft. They are placed at the first and last observation points for flight safety. Therefore, they must have the proper reflexes, the necessary training, correct reactions, and attitude. It is not easy to be a well-equipped staff member in every aspect. Some of these features are acquired through education, some through experience, and some through communication and awareness-raising or as a result of handling incidents (Dupin et al., 2015).

Ergonomics is all about the component of human factors, which are related to the physical body and related tasks with equipment design. To reduce the number of incidents, it is better to establish an ergonomics program (FAA, 2007). Paying attention to ergonomics makes the management issues meaningful. In this way, work requires less effort, and it takes less time while the work gets more productive. On the other hand, ignoring ergonomics is costly- losing time to the loss of livelihood in the most severe injuries. In order to find a solution to those issues, it is better to redesign the work practices by making the work easier (Seeley, 2009).

Yazgan (2018), in her study, suggested a holistic framework for working environment systems for technicians by developing human risk taxonomy within ergonomics and corporate performance in aviation.

The results of this study may be adapted to other departments of ground handling, so the company can seize the opportunity to identify all risk sources to deal with them before the accident and/or incidents in the airport. The taxonomy developed in this study may contribute to current literature besides supporting the decision-making process of managers while managing human error especially caused by ergonomic factors in ground handling operations.

2. Ergonomic Risk and Risk Assessment

Ergonomics is defined by International Ergonomics Association as "…the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance" (Middlesworth, 2018).

The goals of ergonomic interventions should be determined and explained all over the organization. Although it varies according to the structure of the organizations, the most basic targets are given below (FAA ATA Specification 113- Chapter 7):

- Reduce error
- Few injuries/ illness
- Few health issues
- Productivity
- Better quality

There are some studies in aviation focusing on ergonomics of lifting by the baggage handlers who have workplace injuries on the ramp as Asadi, Mott, and Yu (2019) found that ramp personnel has higher workload and musculoskeletal injury risks. Bern et al. discussed the relationship between heavy lifting in awkward positions and the risk of pain. They observed 3092 baggage handlers. The study showed that the baggage handlers highly self-reported musculoskeletal symptoms during the last 12 months in the neck, shoulders, elbows, wrists, hips, and knees compared to the non-baggage handlers (Asadi, Mott, and Yu, 2019).

As the importance of human resources in management develops, its reflections on aviation applications have been noticed recently. The relationship between man, machine, and the number and cause of mistakes made it the centre of attention of researchers. The concepts of the human factor and ergonomic have close connections. The word "ergonomic" is preferred by European countries, Australia, and New Zealand, and the term "human factor" is used by Americans (Uchroński, 2020).

In the aviation industry, in the "man–machine–environment" ergonomic model, human plays an essential role. For instance, pilots are important in all phases of an aircraft operation. The role of human may either be positive or negative by bringing an undesirable air event or correcting a negative action in a specific task situation. Time, skill, knowledge, technology are the main elements being in a positive or negative role in all situations, threatening the safety of the task. Thus, the concept of the human factor should be perceived in the relations between man-operator (pilot, air controller, aviation mechanic, etc.) and other areas appropriate for the operation of machines (aircraft) (Uchroński, 2020).

Ergonomic risk factors are related to the job aspects and may impose biomechanical stress on the worker, and those risk factors as synergistic elements may cause hazards (Iowa State University, 2021).

Ergonomic risk is underlined primary issue which is associated with the work environment. The main ergonomic risk factors resulting from job activities are listed below (UC San Diego, 2021).

- Awkward postures
- Bending
- Compression or contact stress
- Forceful exertions
- Insufficient rest breaks
- Lifting
- Lighting
- Noise
- Pushing, pulling
- Reaching
- Repetitive motions
- Static or sustained postures
- Temperature extremes
- Vibration

Baggage handling, for instance, involves similar tasks at all larger airports and is, characterized by heavy lifting, pushing, and pulling on the ground, and work in constrained and awkward postures, such as sitting, stooping, kneeling, and lying down (Bergsten, 2017). Stretching, reaching, and lifting may contribute to physical fatigue (ICAO, 2002). Ground operation workers need to kneel and do heavy handling while in a kneeling posture presents the greatest risk of back injuries (Riley, 2009). Ground handlers need to push and pull baggage cards, belt loaders, and aircraft steps while manually loading aircraft bulk holds. While insufficient rest breaks may increase the illnesses, short rest periods spent lying down will improve spinal cord nutrition (Riley, 2009).

Physical factors related to performing the required tasks, such as strength, height, reach, vision, and hearing, are significant and affect the individual performance. While designing the workplace, normal human physical differences must be considered. Individual tolerances for the differences in heat, pressure, light, noise, vibration, time of day, etc., need to be recognized (ICAO, 2002).

Working outdoors on a ramp, ground handling staff faces variations in temperatures, wind, noise, visibility, and lighting work surfaces. These factors affect physical well-being and create conditions for committing operational errors (ICAO, 2002).

Human error can be controlled by minimizing the probability of errors and reducing the consequences of any errors through cross-monitoring and crew cooperation. High levels of competence, proper checklists, procedures, manuals, maps, charts, and reducing noise, vibration, temperature extremes, and other stressful conditions may help control the probability of incidents/errors. Training programs that increase the cooperation and communication between crew members will also reduce the probability of errors. Equipment design to make errors reversible, and equipment that monitors or complements and supports human performance, also contribute to limiting errors and their consequences (ICAO, 2002)

Understanding and trying to predict human performance and limitations are fundamental issues of human factors. As in the other industries, in aviation management, considering of human factors has progressively developed and been refined, and this led to enhancing the safety in aviation operations today (ICAO, 2002). In addition to understanding human performance, physical job activities, workplace conditions, equipment characteristics, and workstation environmental conditions are very important (IOWA State University, 2021).

Ergonomic risk factors are explained as working conditions and/or operating processes that may contribute to the risk of developing work-related musculoskeletal disorders (MSDs). This includes damaged muscles, nerves, tendons, ligaments, joints, cartilage, or spinal disks (EMC, 2021). According to Middlesworth (2018), the major workplace ergonomic risk factors to consider are; forceful exertions, repetitive awkward postures, and repetition of high tasks.

Some ergonomic risk factors are certain and easy to identify however some are not as apparent or observable. So, employers should be ready to manage risk factors in the workplace via training and experience. Developing and implementing the ergonomics programs, staff may gain a proper working knowledge of the ergonomic risk factors related to workplaces (Iowa State University, 2021).

Ergonomic risk assessment is a proactive approach to occupational health and safety, which includes identifying the hazard, estimating the risk (likelihood and severity of harm), and making recommendations to control the risk where necessary (University of Cape Town, 2021).

Risk assessment is the process of risk analysis and risk evaluation. Risk analysis is the use of available information to identify hazardous tasks and to estimate the risk. Risk evaluation is the process based on the risk analysis but considering other factors, such as economic and social, in which judgments are made on the acceptability of the risk.

3. Ergonomic Risk Factors in Ground Handling Operations

Ground handling staff face several challenges such as stress, tight turnaround times, safety standards shift, and night work in their daily work (Contego Aviation, 2018). Ground handlers are also exposed to de-icing chemicals, hydraulic fluids, jet fuel, and exhaust fumes which are risky for human health. Proper training and information on hazardous substances help to protect the staff and are crucial to minimizing potential risks.

On the other hand, baggage handlers using belt loaders are at risk of musculoskeletal diseases. Training and regular monitoring of workers are necessary to minimize these occupational problems (Contego Aviation, 2018).

In this section, significant ergonomic risk factors in ground handling operations are briefly explained.

Table 1. Taxonomy of Ergonomic Risk Factors

Main categories	Sub-categories
Scheduling workload	shift work staff shortage time pressure
Mental conditions	stress out of control loose concentration
Physical strength	vision/hearing loss fatigue musculoskeletal disorders
Qualifications	knowledge/skills expectancies communication

A taxonomy of ergonomic risk factors for ground handling operation is developed under **four main categories** as; scheduling workload, mental conditions, physical strength, and qualifications. The supporting sub-categories of these main categories are shown in Table 1 (Luxhøj et al., 2001; Sari, 2015).

1. *Scheduling workload:* The physical and mental workload affects the health and performance of the ground handling personnel. The level of total workload is significantly affected by environmental and organizational factors as well as mental and physical factors.

The physical workload is also defined as the factors that are related to the biomechanical strains that occur in the body (Westgaard and Winkel, 1996). When any personnel works with a physical workload above their physiological capacity for a long time, it causes work accidents, faulty production, and health problems.

Mental workload is a concept formed by mental and perceptual activities such as calculation, decision making, remembering, and research (Delice,2016). Mental workload is the amount of mental work required to complete a task over a period of time. It appears when the requirements of a job and the skills, behaviors, and perceptions of the employees do not match each other (Emeç and Akkaya,2018).

Airline ground handling global standardization is essential for sustainability as emergencies and irregular shifts may increase work pressure, affecting individual health, corporate performance, and safety (Sun and Chiou, 2011).

Scheduling workload is a significant element as much as determining the shift work for the ground staff; if there is a shortage of staff under the time pressure operations, individuals have the potential to cause accidents and hurt themselves. Shift work is a source of occupational stress. Aviation is a 24-hour industry. This reality creates problems for many employees, such as ground crew, flight mechanics, and security personnel (Kushnir,1995).

Shortage of qualified staff is another important factor like time pressure and workload. There are several reasons for staff shortage, such as low pay and poor working conditions or unqualified personnel varying from country to country. Thus, a limited workforce has to take responsibility for the excessive workload (ICAO, 2002). The International Air Transport Association (IATA) stated that more than 50% of ground handling activities worldwide are handled by more than 1000 ramp handlers (iJET, 2021).

Time pressure affects the performance of an individual, which in turn can place the individual in a situation of committing an error (Kushnir,1995). The reason for the increase in demand for air transport is that it is the fastest transportation mode. To cover the demand, the industry faces constant time pressure and cost pressure. Faster turnaround times are also affecting the effectiveness of personnel and ground handling operations as well.

2. *Mental conditions*: The mental conditions of the personnel affect the performance depending on the reasons such as workload and time pressure. According to Luxhøj and Coit (2006), principal mental conditions were stress and anxiety, overconfidence, loss of situational awareness, and task saturation due to an event overload.

Stress is a diffuse and global negative experience accompanied by other negative emotions such as anxiety, frustration, dissatisfaction, and depression (Kushnir,1995). In the 1980s, stress-related illnesses accounted for more than 14% (Raymond, 1988). Today, more and more people are becoming sick due to illnesses caused by stress (Harnois and Gabrie, 2000).

Out of control: The requirements of the working environment for ground handling are treated as stressors that cause stress. Intelligence, skill, knowledge, personality, and experience in stress-inducing situations are defined as the characteristics of personnel in developing coping strategies (Uchroński, 2020). The deterioration of the individual’s functioning under stress increases the possibility of the wrong decision.

Loose concentration is caused by many reasons such as light, noise, other people, stress, fatigue, and more can be listed for ground handling staff. Lack of concentration or distraction is probably the biggest cause of traffic accidents and safety incidents and needs to be focused on (Techathammawong, 2016).

3. *Physical strength* of ground operations agents may be negatively affected by the aircraft movement on the ground. The noise may cause hearing from minor to permanent; the dust can cause eye irritation; fatigue may result in hurt, injury, and stress. Due to high work stress, shortage of staff, and other factors such as weather and excessive working hours, an individual can find himself in an awkward situation. The risk of fatigue exists in all activities of ground operations before the aircraft’s arrival and during the aircraft on the ground (Sari, 2015).

Vision/hearing loss, known as occupational hearing loss, is one of the common work-related injuries in aviation. Noise exposure can be dangerous for pilots, cabin attendants, mechanics, and baggage handlers as they spend a lot of their time on the job in noisy environments. It is crucial to prevent people from long-term exposure for occupational health and safety (Smedje et al., 2011).

Human performance may adversely affect human fatigue, like sleep deprivation, circadian rhythm abnormalities, health-related tiredness, and task-induced influences (Bendak and Rashid,2020). These adverse effects may lead to aircraft accidents.

Excessive working hours can cause musculoskeletal disorders. If the staff works in the same position for a long time, the person loses their body form and flexibility after a while, and recurrent pain occurs. It is very important to make work and workplace arrangements by using ergonomic analysis methods in order to prevent health problems caused by long working hours, increased stress, irregular working environments, and unsuitable environmental factors and to reduce total workloads (Adar and Delice, 2019).

4. *Qualifications*; every individual has different personality traits that are out of the control of top-level management. An individual's performance level could be affected by some personal factors such as background knowledge and trained skills, expectancies, communication abilities (Luxhøj et al., 2001).

Ground handling services include a wide range of tasks using several different types of equipment. Agents need to be sure that all the tasks are done properly in a coordinated way. Knowledge is power in the aviation industry; if the agent has the right job knowledge, it will help to minimize the risks, to do the job effectively, which results in satisfied customers.

A skill is an organized and coordinated pattern of psychomotor, social, linguistic and intellectual activity. Teaching is a skill in its own right, and the possession of skill in a particular activity does not necessarily indicate skill in teaching that activity to others. This is an important consideration in the selection of flight instructors, check pilots or anyone connected with a teaching activity. Skills, knowledge or attitudes gained in one situation can often be used in another. This is called positive learning transfer. Negative learning transfer occurs when previous learning interferes with new learning. It is important to identify the elements of training that can induce negative learning transfer since a return to earlier learned practices may occur in stressful situations (ICAO, 2002).

Expectancies: A frequently cited causal factor in aviation accidents is "expectancy"; i.e. individuals see what they want to or expect to see and hear what they want to or expect to hear. Auditors too are subject to the normal psychological process of expectancy, which is a form of conformity bias (ICAO, 2002 Doc 9806 AN/763)

Effective communication helps transfer essential information for operational safety. Transferring information may be verbal, written or via symbols and body gestures. The quality of communication is adversely affected by unclear or ambiguous messages, background noises, messages misinterpreted, impaired hearing, or non-native speakers (ICAO, 2002).

Miscommunication and misunderstanding among employees or between employee and supervisor may contribute to accidents/risk occurrence during operations.

Another significant factor observed is the training, which may directly affect the factors. Inadequate training for operation and the lack of comprehensive crew training had a vital effect on decision-making abilities (Luxhøj and Coit, 2006).

Training is a process aimed at developing specific skills, knowledge, or attitudes for a job or a task. On the other hand, lack of proper training may cause the sequence of unsafe acts. (ICAO, 2002).

Training is especially important for increasing situational awareness, and it is one of the fundamental parts of managing ergonomic risks. Ergonomic awareness training should consist of the following (the University of Cape Town, b, 2021):

- Identify the signs and symptoms of work-related musculoskeletal disorders (WMSDs) and the importance of early reporting.
- Recognize workplace risk factors for WMSDs and understand general methods for controlling them.
- Recognize the employee's role in the process; employees know their jobs better than anyone else knows and are often the source of ideas to improve them.
- There should be open interaction between trainers and trainees.
- Employees need to know the procedure for reporting ergonomic risk factors and musculoskeletal disorders.

The best ergonomic solutions are based on the expertise of the workers. They know their bodies and can best identify what activities take the most tolls and effort.

In this study, ergonomic risk factors in ground handling operations are developed by reviewing the literature (Chang and Wang, 2010; Toriizuka,2001, Rankin et al.,2000; Reason, 2000; Reason, 1997; Fogarty, 2004) and taking experts opinions on human performance.

4. Conclusion

As stated by most of the studies, the human factor is still the weakest part of the aviation system, especially in accidents and incidents, so it is fundamental to carry out permanent preventive activities related to human factor for improving flight safety, As a result of ergonomic risk factors faced by ground handling personnel, which is the main subject of this study, it is essential to determine risk factors, complete the necessary training and take precautions in order to prevent both loss of life and property and accidents (Uchroński, 2020).

In this study, ergonomic risk factors are developed by considering the related literature and taking experts' opinions.

The taxonomy developed in this study may provide to the manager making accurate and timely decisions. Especially, the managing ergonomic factors, as a decision-making problem, always exists at the top manager's agenda. Ground handling operational managers need decision-making processes to help them understand interactions in today's multivariate business environment.

In this study, to reach an effective and applicable taxonomy example for ground handling operations in Turkey, online interviews are conducted with one ramp supervisor, three academic staff, and two graduate program students via Zoom. In this taxonomy, all possible risk factors related to the ground handling operation are classified into four main groups as "scheduling workload, mental conditions. physical strength and qualifications". All these main groups are divided into sub-factors. Those are "shift work, staff shortage, time pressure, stress, out of control, lose concentration, vision/hearing loss, fatigue, musculoskeletal disorders, knowledge/skills, expectancies, communication", which are also critical to prevent error-based business interruptions, fault-induced accidents, and crashes resulting high economic losses and fatal.

This study has limitations on ergonomic factors to be examined. However, risk factors affecting corporate performance depend on various fields such as managerial decision skills, equipment, and technology, human resources, investments, communication with partners, etc. For this reason, in the future study, not only ergonomic risk factors but also organizational, human resources, and sustainability risk factors can be studied. With the help of risk analysis and multi-criteria decision

Abbreviations

CPM	:	Corporate Performance Management
HRM	:	Human Resource Management
MSD	:	Musculoskeletal Disorders
IATA	:	International Air Transport Association
WMSD	:	Work-Related Musculoskeletal Disorders

CRediT Author Statement

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