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AIRCRAFT TAKE-OFF MASS ESTIMATION IN AVIATION INCIDENT INVESTIGATION PROCESS

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Abstract. *Analysis of existing techniques of aircraft take-off mass estimation in the process of aviation incidents investigation was made. Aircraft take-off mass estimation technique was suggested. It uses parametric information from a flight data recorder that does not need previous parameters filtration, making an obtained estimation more effective. Effectiveness was demonstrated on specific aviation incident example.*

Keywords: aircraft; a priori information; aviation incident; flight data recorder; indicated speed; initial time shift estimation; parametric information errors; take-off mass; take-off mass estimation.

1. Introduction

One of the main objectives of aviation incidents investigation is to find out list of the key factors that caused aviation incident. The reference point of such investigation is an aircraft take-off mass estimation prior to aviation incident. Familiarity with this parameter helps to explain aircraft behavior in the process of aviation incident development. It is known, that loading magnitude and cargo distribution along the length of the aircraft's fuselage influence on changing of aircraft performance and characteristics of stability and control. Therefore development of aircraft balance and mass estimation algorithms is a relevant problem in the aviation incidents investigation process.

The flight data recorders allow obtaining of the information about changing of linear and angular velocities of flight, flight altitude, deflecting of flight control surfaces, aircraft systems condition. This information keeps in secured flight data recorders and after processing using ground-based complex becomes the foundation to ascertain the cause of aviation incident.

2. Analysis of publications

There is a great deal of algorithms for aircraft mass estimation using parametric information data. These algorithms are based on application of equations of the aircraft motion for particular phase of flight. Works [4, 6, 7] demonstrate algorithms, which use equations of motion for take-off phase, climb phase, cruise phase. Usage of specific flight phase helps to simplify equation of motion greatly (decrease a number of degrees of freedom) and correctly take into consideration a priori information about aircraft propulsion and aerodynamic characteristics.

Aircraft mass estimation by means of mathematical model of motion using information from flight data recorder is inverse problem of flight dynamics. It means that it is necessary to find out coefficients of mathematical model with already obtained solution. As opposed to the direct problem, the inverse problem in general view is not correct according to Tikhonov [10]. Incorrectness is caused by both errors of a priori information about aircraft and propulsion and errors in registered parametric information.

Consequently, development of aircraft take-off mass estimation techniques, which are based on parametric information, is relevant for the procedure of ascertaining of an aviation incident reason.

3. Mathematical modelling of aircraft take-off run

Modelling of aircraft take-off run carries out in velocity-oriented coordinate system $OX_\alpha Y_\alpha Z_\alpha$. Take-off run is a linear non-steady motion. Forces, which act on an airplane during a take-off run, are presented in Fig. 1. Additionally during a ground take-off run, bearing reactions – tangential F_ζ and normal F_n, applied to undercarriage wheels, also act on an airplane. Tangential bearing reactions are connected with normal ones with rolling friction coefficient

$$F_\varsigma = f \cdot F_n . \quad (1)$$

Value of rolling friction coefficient f depends on runway conditions and varies in wide range [5]. Considering chosen coordinate system, projections on OX_α and OY_α axis of forces acting on an airplane represent in such a form:

$$\sum F_{iXa} = P_p\cos\alpha_p - X_a - F_\varsigma - mg\sin\theta = m\frac{dV}{dt};\quad\quad (2)$$
$$\sum F_{iYa} = Y_a + P_p\sin\alpha_p + F_n - mg\cos\theta = 0,$$

where P_p – total thrust of running engines; α_p – angle of engines incidence in a vertical plane; F_ς – tangential force from rolling friction of wheels of main and nose landing gear on the runway surface; $F_\zeta = F_{\zeta_{m\lg}} + F_{\zeta_{n\lg}}$; F_n – normal force from reaction of wheels of main and nose landing gear on the runway surface; $F_n = F_{n_{m\lg}} + F_{n_{n\lg}}$; θ – angle of inclination runway surface with respect to horizon. Expression for F_n evaluation is obtained from the second equation of the system. Substitution of this expression into the first equation of the system using relation (1) yields:

$$m\frac{dV}{dt} = P_p\cos\alpha_p - X_a - -f\left[mg\cos\theta - Y_a - P_p\sin\alpha_p\right] - mg\sin\theta. \quad (3)$$

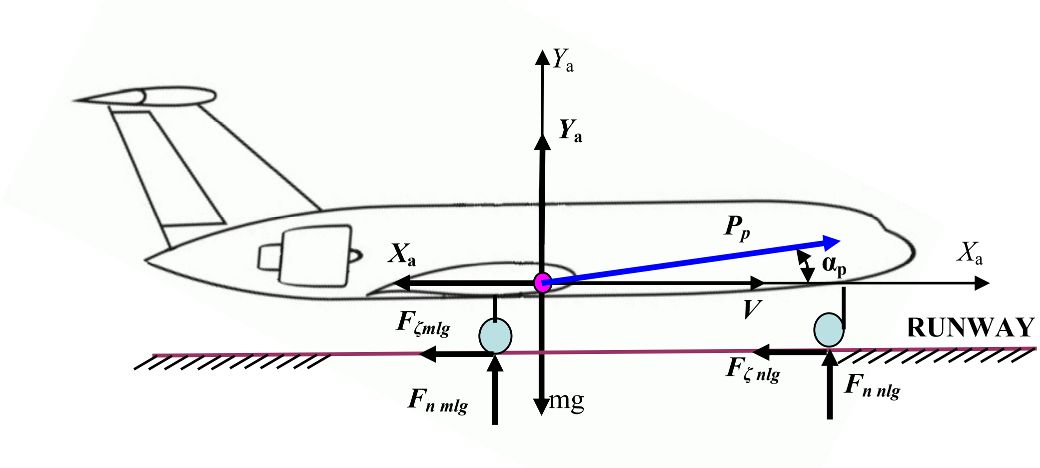


Fig. 1. Forces that act on an airplane during take-off run

Approximation of total thrust change over take-off run speed by a quadratic polynomial

$$P_p = P_0 + P^V V + P^{V^2} V^2 \quad (4)$$

Expression of aerodynamic forces using non-dimensional aerodynamic coefficients is given by $X_a = c_{xa}\frac{\rho S}{2}V^2$, $Y_a = c_{ya}\frac{\rho S}{2}V^2$. Taking into account these transformations, equation (3) becomes

$$m\frac{dV}{dt} = P_0\cos\alpha_p + P^V V\cos\alpha_p + +P^{V2}V^2\cos\alpha_p - c_{xa}\frac{\rho S}{2}V^2 - -fmg\cos\theta + fc_{ya}\frac{\rho S}{2}V^2 + +fP_0\sin\alpha_p + +fP^V V\sin\alpha_p + fP^{V2}V^2\sin\alpha_p - mg\sin\theta. \quad (5)$$

Combining the equation (5) coefficients by power of speed yields

$$m\frac{dV}{dt} = A + BV + CV^2, \quad (6)$$

where

$$A = P_o\left(\cos\alpha_p + f\sin\alpha_p\right) - mg(f\cos\theta + \sin\theta),$$
$$B = P^V\left(\cos\alpha_p + f\sin\alpha_p\right),$$
$$C = P^{V^2}\left(\cos\alpha_p + f\sin\alpha_p\right) + \left(c_{ya}f - c_{xa}\right)\frac{\rho S}{2}.$$

Equation (6) describes variation of acceleration during take-off run. To proceed to the change of speed at this phase, it is necessary to integrate both left and right sides of this equation

$$m\int\frac{dV}{dt} = \int A + BV + CV^2. \quad (7)$$

After alterations equation (7) becomes

$$\int\frac{dV}{A + BV + CV^2} = \frac{1}{m}\cdot\int dt, \text{ or}$$

$$\int\frac{dV}{A + BV + CV^2} - \frac{1}{m}\int dt = \text{const}. \quad (8)$$

The left hand side of expression (8) is an indefinite integral that has analytical solution [9]

$$\int \frac{dV}{A+BV+CV^2} = \frac{1}{\sqrt{-\Delta}} \ln \frac{B+2CV-\sqrt{-\Delta}}{B+2CV+\sqrt{-\Delta}},$$

where $\Delta = 4AC - B^2$.

The following notation serves for simplification of calculation

$K = \sqrt{-\Delta} = \sqrt{B^2 - 4AC}.$

Taking into account these transformations, equation (7) can be written down as

$$\frac{1}{K} \ln\left(\frac{B+2CV-K}{B+2CV+K}\right) - \frac{1}{m} \cdot t = \text{const} . \qquad (9)$$

Equation (9) with initial conditions $t = 0$ $V(0) = 0$ is as follows

$$\frac{1}{K} \ln\left(\frac{B-K}{B+K}\right) = \text{const} . \qquad (10)$$

General equation, that describes aircraft variation of speed during take-off run, is given as

$$\frac{1}{K} \ln\left(\frac{B+2CV-K}{B+2CV+K}\right) - \frac{1}{m} \cdot t - \frac{1}{K} \ln\left(\frac{B-K}{B+K}\right) = 0 . \qquad (11)$$

Making following transformations of the equation (11)

$$\ln\left[\frac{B^2+2(B+K)CV-K^2}{B^2+2(B-K)CV-K^2}\right] - \frac{K}{m} t = 0 \text{, or}$$

$$e^{\frac{Kt}{m}} = \frac{B^2+2(B+K)CV-K^2}{B^2+2(B-K)CV-K^2} . \qquad (12)$$

Equation (12) can be solved for take-off run speed. This gives an opportunity to get the expression for instant take-off run speed depending on operational factors

$$V = \frac{\left(1-e^{\frac{Kt}{m}}\right)(B+K)}{2C\left[e^{\frac{Kt}{m}} - \left(\frac{B+K}{B-K}\right)\right]} . \qquad (13)$$

Using this algebraic equation it is possible to compute value of take-off run speed V for each time of take-off run t and appropriate operational factors. Aerodynamic coefficients compute for instant angle of attack value. Power plant characteristics specify antecedently from Flight Manual of the aircraft with approximation of altitude-velocity performance by means of quadratic polynomial (4). Operational factors values are chosen from a flight data recorder passport (outer air temperature at the take-off aerodrome, air density, velocity and direction of a wind relative to a runway, friction coefficient, take-off course, balancing and aircraft take-off mass value) and from a reference book about air navigation information by an aerodrome name (aerodrome altitude above sea level, angle of inclination of a runway surface, runway length).

4. Aircraft take-off mass estimation

Computation of an aircraft mass makes on a basis of recorded flight information. There are different methods of searching parameters estimation, which differ by a using optimality criterion and a priori information about an object. In general, choice of an optimality criterion is subjective, while estimation procedure substantially depends on a chosen criterion.

In most cases criterion of an identification quality is chosen as quadratic. It expresses in the form of an integral value of a squared deviation

$$\begin{aligned} J(V^*,\ V_{\text{м}},\ \beta) &= \sum_{j=1}^{N} e^2(t_j) = \\ &= \sum_{j=1}^{N} (V^*(t_j) - V_m(t_j,\beta))^2 \end{aligned} , \qquad (14)$$

where t_j – discrete values of an instant time of an aircraft take-off run ($j = 1,\ 2, \ldots, N$), $V^*(t_j)$ – registered values of an indicated aircraft take-off run speed, $V_m(t_j,\beta)$ – speed value computed with model (13), β – sought-for parameters vector (t_0, m – initial time estimation of experimental data processing and aircraft mass estimation). Initial time of experimental data processing t_0 is specified by possibility of certain registration of an aircraft take-off run speed using pitot-static system (usually it's a speed value of 50 ÷ 80 km/h).

Search of the sought-for parameters vector β values consists in a search of a minimum criterion (14) value using one of the optimization methods with no limitations

$J(V^*,\ V_{м},\ \beta) \Rightarrow \min\limits_{\beta}$.

Existing optimization algorithms with no limitations can be divided into two groups: gradient methods and non-gradient methods. To solve the given problem it's expedient to use non-gradient methods (for example, simplex Nelder–Mead method [8]), for which there are no need to compute gradient values of function analytically or numerically. In addition, important factor in favor of these methods is no restrictions on the type of objective function. In Matlab package, this method is implemented as a built-in function **fminsearch**.

Software complex, which allows estimating sought-for parameters t_0, m was created in the applied program package Matlab. Software complex included modules for aerodynamic coefficients computation, considering instant angle of attack, flap position etc. General algorithm of coefficient computation is as follows

$$c_{ya} = c_{y\,\mathrm{main}} + \Delta c_{y\mathrm{wb}} + \Delta c_{y\,\mathrm{st}} + \Delta c_{y\,\mathrm{el}} + \\ + \Delta c_{y\,\mathrm{ail}} + \Delta c_{y\,\mathrm{GE}},$$

$$c_{xa} = c_{x\mathrm{main}} + \Delta c_{x\mathrm{st}} + \Delta c_{x\,\mathrm{el}} + \Delta c_{x\,\mathrm{ail}} + \Delta c_{x\,\mathrm{lg}} + \\ + \Delta c_{x\,\mathrm{rud}} + \Delta c_{x\,\mathrm{GE}},$$

where $c_{y\,\mathrm{main}}$, $c_{x\mathrm{main}}$ – general lift (drag) coefficient, which is defined by an angle of attack and flap position with no consideration of wing blowing by propeller; $\Delta c_{y\mathrm{wb}}$ – increment of a lift coefficient defined by wing blowing by propeller; $\Delta c_{y\,\mathrm{st}}$, $\Delta c_{x\mathrm{st}}$ – increment of a lift (drag) coefficient defined by stabilizer deflection; $\Delta c_{y\,\mathrm{el}}$, $\Delta c_{x\,\mathrm{el}}$ – increment of a lift (drag) coefficient defined by elevator deflection; $\Delta c_{y\,\mathrm{ail}}$, $\Delta c_{x\,\mathrm{ail}}$ – increment of a lift (drag) coefficient defined by an angle of aileron deflection; $\Delta c_{y\,\mathrm{GE}}$, $\Delta c_{x\,\mathrm{GE}}$ – increment of a lift (drag) coefficient defined by ground effect; $\Delta c_{x\,\mathrm{lg}}$ – increment of a drag coefficient defined by landing gear strut; $\Delta c_{x\,\mathrm{rud}}$ – increment of a drag coefficient defined by rudder deflection. Antecedent information about components of these coefficients was obtained from the atlas of specific aircraft aerodynamic characteristics.

To compute coefficients P_0, P^V, P^{V2} the information about altitude-velocity performance of the power plant at take-off conditions of specific aircraft, which was obtained from technical specification, and built-in function **polyfit** were used.

In addition, the module that allowed erasing anomalies from flight information records had been developed. The module algorithm uses Tukey's procedure (Tukey 53X) [2].

5. Exploration of measuring systems and antecedent information errors influence on take-off mass estimation

Aircraft take-off mass estimation is carried out based on information, that is received from flight data recorders and a priori information that is necessary to calculate an instant aircraft take-off run speed (13). This is information about take-off run speed variation, angle of attack variation, variation of control surfaces deflection angles, engine thrust value, aerodynamic coefficients value, rolling friction coefficient value, runway angle of incline value, wind velocity and direction value, outer air temperature (air density). This information can include both systematic and random errors.

Influence of above-mentioned factors errors on take-off mass estimation m and t_0 we will explore by making the computational experiment by the example of An-24 take-off run with take-off mass of 21000 kg. A priori data about aerodynamic characteristics and the power plant characteristics of An-24 was utilized from work [1]. Computation of An-24 speed variation at take-off run phase was executed using expression (13). Take-off run track from start to the moment of nose gear lift-off was calculated. Take-off execution technology was modeled according to the technology, which was described in work [10]. Operational factors values were chosen as follows:

- calm take-off conditions;
- take-off engine operation;
- flaps position – 15°;
- nose gear lift-off speed is 210 km/h;
- value of a rolling friction coefficient is 0,03;
- temperature of outer air is 15 °C;
- runway angle of incline is 0°;
- elevator angle of deflection is -8°;
- ailerons and rudder are in neutral position.

The graph of speed variation in time made for above-mentioned conditions is represented in Fig. 2.

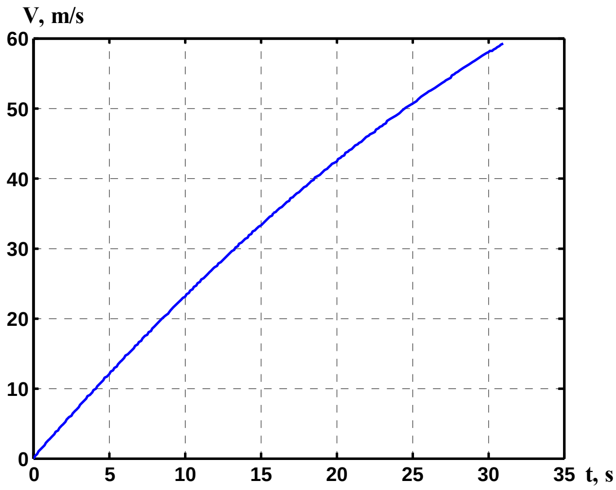


Fig. 2. Variation of An-24 take-off run speed with mass of 21000 kg.

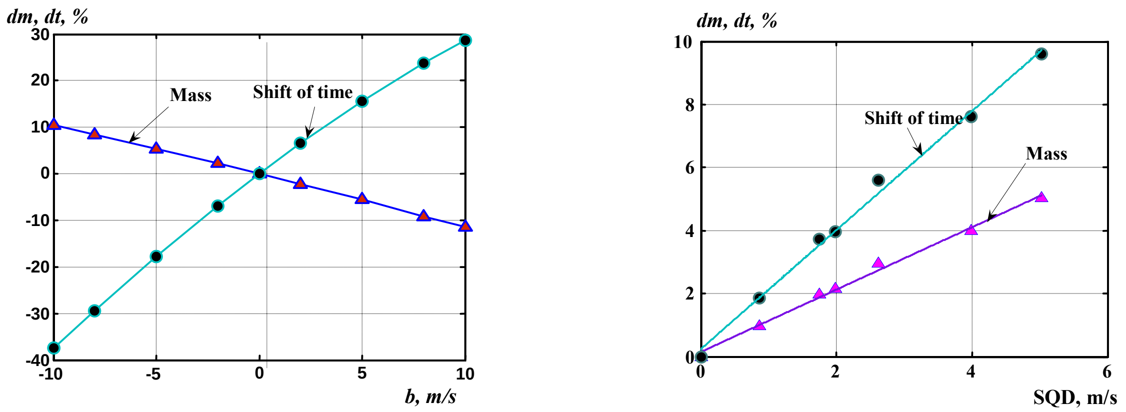
To test obtained program, complex origin value was selected as t_0=10 s. It gives indeterminate area by speed equal to 23,1 m/s (83,2 km/h). Thereby, take-off run track took 20,25 s. The obtained dependence was a reference in respect of which systematic and random errors, which are connected with flight data recorders operation, were input. To analyze component errors influence on the result of the mass evaluation m and initial time t_0, distortion of a take-off run speed value was created using algorithm

$$V_{\text{dist}} = V^* + b + \xi,$$

where V_{dist} – speed of aircraft distorted by the amount of random and systematic errors; V^* – speed of aircraft take-off run at the time interval 10÷23,1 s (see Fig. 2); b – value of a systematic error component (if it's not considered, it can be equal to the longitudinal component of wind velocity); ξ – random error component of a take-off run speed. Random error component was specified by squared deviation of stochastic Gaussian process that was generated by **randn** program. In computational experiment, value of a systematic error component was specified in -10,0÷10,0 m/s range, while the squared deviation was specified from 0 to 5 m/s. Computation of mass estimation m and t_0 using distorted take-off run velocity vector V_{dist} was made. Relative values of initial time and mass estimation shift were calculated using dependencies

$$dm = \frac{m_0 - 21000}{21000} \cdot 100, \ [\%]; \qquad dt = \frac{t_0 - 10}{10} \cdot 100, \ [\%], \tag{15}$$

where m_0, t_0 – parameters estimations, obtained with optimization of the criterion (14) process, using distorted take-off run velocity vector. Dependence of systematic and random components of error influence on initial time and mass estimation shift is represented in Fig. 3.



a *b*

Fig. 3. Influence of take-off run speed error value on initial time and mass estimation shift: *a* – systematic error; *b* – random error

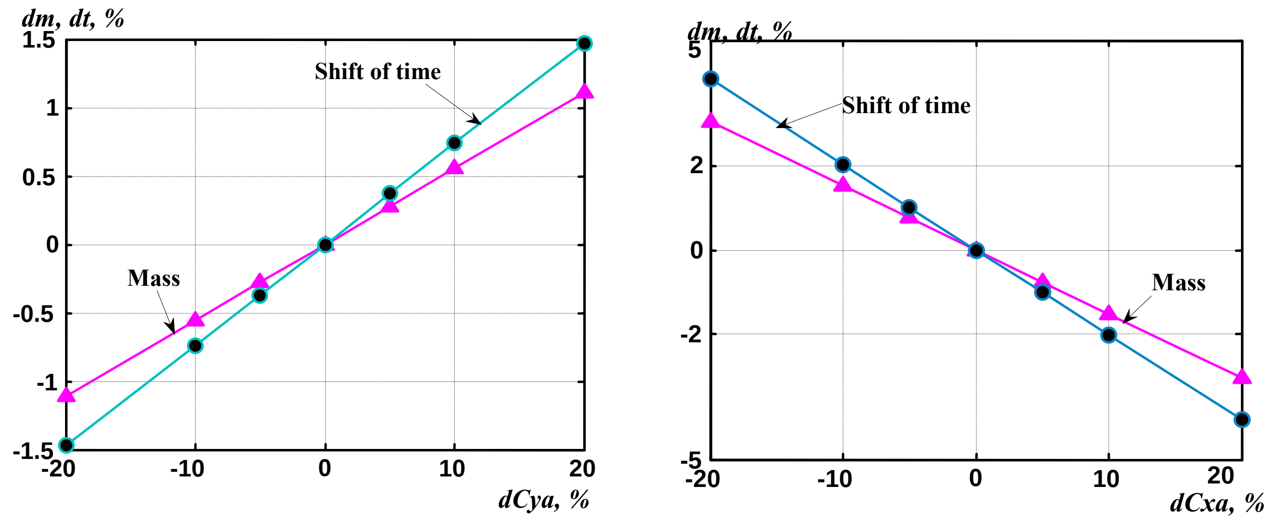
Analysis of graphs, represented in Fig. 3, reveals that a technique of mentioned parameters estimation is more sensitive to the systematic error. It means that neglect of the longitudinal component of wind can cause a significant shift of initial time and aircraft mass estimation. Thereby, neglect of head (tail) wind velocity equal to 5 m/s results in shift value of initial time estimation of ~ 16 % and mass estimation shift value of ~7 % (see Fig. 3). Sensor, which measures aircraft speed (for FDR-12 system), has fiducial error of 5 %. It can cause maximum value of random error equal to 10,1 m/s. Taking into consideration a random error distribution law, the squared deviation of this value is 3,4 m/s. The random error, considering the squared deviation equal to 3,4 m/s, results in shift value of initial time estimation of 6,0% and mass estimation shift value of ~3,1 % (see Fig. 3 b).

Influence of a rolling friction coefficient and thrust on the stand designation errors on initial time and mass estimation shift is represented in Fig. 4. As is well known, engine thrust decreases during the exploitation of the aircraft. That is why the error of thrust on the stand designation is negative.

As shown in graphical dependency, thrust on the stand designation error influences on mass estimation of the aircraft shift significantly. Thereby, an error equal to 5 % (engines thrust decreasing of 5% during the exploitation) cause the decreasing of aircraft mass estimation of ~-7 %, while the initial time shift is equal to merely ~-2,2 % (see Fig. 4, *a*).

Error of rolling friction coefficient (runway condition) designation influences on initial time and mass estimation shift insignificantly. Thereby, an error of rolling friction coefficient equal to 20 % cause the mass estimation shift value of ~1,8 %, while the initial time shift is equal to ~0,6 %.

Influence of aerodynamic coefficients (c_{ya}, c_{xa}) designation error on initial time and mass estimation shift was also explored. Graphical relationships that represent this influence are shown in Fig. 5.



a *b*

Fig. 5. Influence of aerodynamic coefficients designation error on initial time and mass estimation shift: *a* – designation error of c_{ya} coefficient; *б* – designation error of c_{xa} coefficient

Analysis of dependencies reveals that influence of lift coefficients designation error on initial time and mass estimation shift is insignificant. Thereby, an error of coefficient designation equal to 10 % cause the mass estimation shift of ~0,6 %, while the initial time shift is equal to ~0,6 % (see Fig. 5, *a*). Designation error of drag coefficient has a little more influence. Thereby, according to Fig. 5, *a*, designation error of drag coefficient equal to 10 % cause the mass estimation shift value of ~1,8 %, while the initial time shift is equal to 2 %.

Analysis of above-mentioned errors revels that the greatest influence on shift of the aircraft mass estimation have thrust on the stand designation error, then systematic error of the speed information (can be caused by neglect of the longitudinal component of wind) and random error component. All other above-mentioned errors have insignificant influence on shift of the aircraft mass estimation that is less than 2 %.

6. Evaluation of technique efficiency using real flight information

To confirm the efficiency of the developed technique, computation of take-off mass estimation of An-24RV (№ 46622), that wrecked at Donetsk International Airport on February 13, 2013 was made. Parametric recorder FDR-12 and voice recorder VR-61 data was used for investigation. Due to utilization of the solid-state drive on the airplane, parameters were registered with frequency value from 2 to 16 Hz. Thus, change of a flight altitude (barometric altitude channel) and an indicated airspeed was registered with frequency equal to 2 Hz, while control surfaces angles of deflection and roll angle with frequency of 8 Hz. The segment of aircraft take-off run track from the moment, when the indicated speed value is equal to 100 km/h (instant time 18 h 14 m 52 s) to the moment of the aircraft lift-off from a runway (instant time 18 h 15 m 34 s) was chosen for the computation.

The moment of the aircraft lift-off from a runway was determined using smoothed barometric altitude value. Butterworth digital filter with cutoff frequency equal to 0,025 Hz [8] was used to smooth the parameter. Indicated speed values were not filtered. They were modified by the aerodynamic correction (see Fig. 6.47, 6.48 [3]). Corrected indicated speed values of An-24RV are represented in Fig. 6 (marked by *). Speed was converted from km/h to m/s. A time reference point of this process was set from 0, that corresponds to instant time 18 h 14 m 52 s.

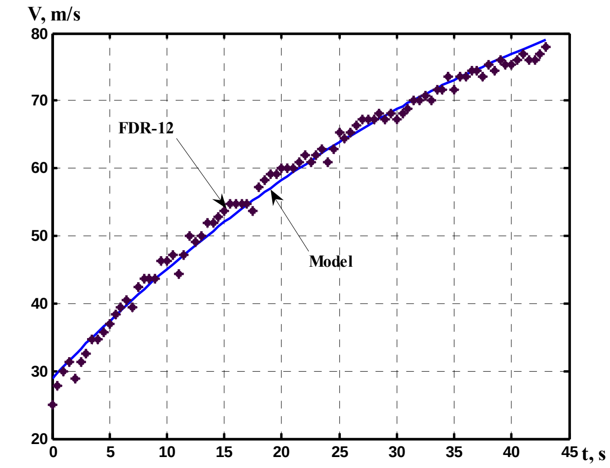


Fig. 6. An-24RV speed variation during take-off run

As a result of the calculations, aircraft mass estimation is equal to 23517 kg and shift of the initial time from the start moment is equal to 14,61 s. Calculation of the take-off run speed was made on the considered take-off track using obtained shift of the initial time and aircraft mass estimation by means of model (13). Speed variation graph is represented in Fig. 6. As shown in the graphs, there is a good correspondence between the registered data and obtained from the model data. Analysis of rests between experimental and model data revealed that they have normal distribution law, which is confirmed by *t* criterion. The bar chart of rests and theoretical distribution function of normal law that is made for estimation of this law are represented in Fig. 7. It confirms that an error in a speed data has a random nature.

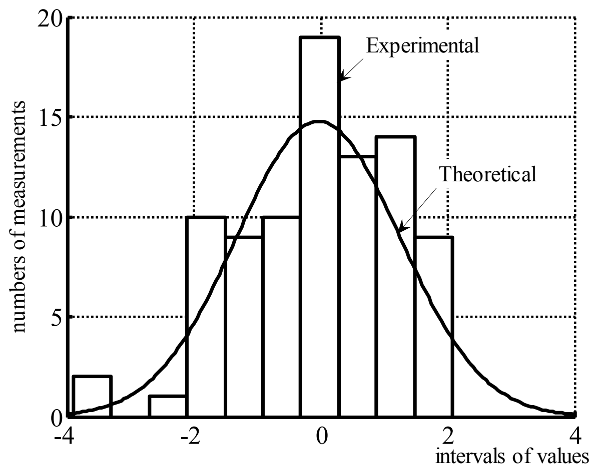


Fig. 7. Distribution density of take-off run speed rests and their approximation using normal distribution law

Analysis of obtained results reveals that suggested technique of aircraft take-off mass estimation provides a stable aircraft take-off mass estimation based an a distorted flight parameters. It allows making a correct analysis of factors that caused an aviation incident. In the demonstrated example of An-24RV wreck, error of take-off mass estimation was 1,2 %. Aircraft accident investigation commission ascertained by means of the loading register that aircraft take-off mass was equal to 23800 kg. This example confirmed an effectiveness of a suggested technique of take-off mass estimation in the process of aviation incidents investigation.

7. Conclusions

According to analysis of existing aircraft take-off mass techniques using parametric information, utilization of analytical methods of solving differential equations that describe behavior of an aircraft during take-off run is expedient. It increases a reliability of obtained aircraft mass estimation significantly.

Aircraft mass estimation errors from indicated speed measurement, choice of power plant a priori information, aerodynamic coefficients and runway condition dependency was designated.

Analysis of errors influence on output information revealed that the greatest influence on shift of the aircraft mass estimation have thrust on the stand designation error and a systematic error of the take-off run speed information.

Obtained results revealed that the developed algorithm of take-off mass estimation allows estimation of actual aircraft take-off mass with acceptable error. Investigation result of An-24RV wreck at Donetsk International Airport with less than 1,2% take-off mass estimation error confirms an effectiveness of the developed technique.

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С. О. Іщенко. Оцінка злітної маси повітряного судна в процесі розслідування авіаційної події

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Розглянуто проблему достовірного оцінювання злітної маси повітряного судна за допомогою інформації від бортових систем реєстрації параметрів руху для проведення розслідування причини авіаційної події. Сучасні методи вирішення такої задачі базуються на попередньому спотворенні отриманої інформації шляхом її фільтрації. Розроблено методику яка для оцінювання злітної маси використовує зареєстрований масив приладової швидкості розбігу без попереднього його опрацювання. Оцінено вплив похибок необхідної для розрахунків апріорної інформації на зсув оцінки злітної маси ПС та початкового часу. Наведений приклад оцінювання злітної маси в процесі розслідування конкретної авіаційної події. Цим прикладом доведено ефективність розробленої методики.

Ключові слова: авіаційна подія; апріорна інформація; бортові засоби реєстрації параметрів руху; злітна маса; повітряне судно; оцінка злітної маси; оцінка зсуву часу; похибки параметричної інформації; приладова швидкість.

С. А. Ищенко. Оценка взлетной массы воздушного судна в процессе расследования авиационного происшествия

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Рассмотрена проблема надежной оценки взлетной массы воздушного судна, на базе информации полученной от бортовых систем регистрации параметров движения, для проведения расследования причин авиационного происшествия. Существующие методы решения этой задачи строились на основе предварительного искажения полученной информации путем ее фильтрации. Была разработана методика, которая для оценки взлетной массы использует зарегистрированный массив значений приборной скорости разбега без предварительной его обработки. Исследовано влияние погрешностей в исходной априорной информации на смещение оценки взлетной массы воздушного судна и смещение оценки начального момента времени разбега. Приведен пример оценки взлетной массы ВС в процессе проведения расследования конкретного авиационного происшествия. Этот пример продемонстрировал эффективность разработанной методики.

Ключевые слова: авиационное происшествие; априорная информация; бортовые средства регистрации параметров движения; взлетная масса; воздушное судно; оценка взлетной массы; ошибки параметрической информации; оценка сдвига начального момента времени; приборная скорость.

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