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Reliability model of a wind tunnel balance system

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Abstract

Balance is one of the most significant and commonly used measurement instruments in wind tunnels. It is thus critical that this instrument is fault-tolerant and reliable. To help in the design of dependable balance systems, one must model and analyze the system from this perspective. We achieved this by considering the structure of a typical balance system and the types of errors it may encounter during operation. We estimated the failure rates of the components of the balance system, such as the balance structure, strain gages, and power supply, using manufacturer technical documents and fatigue tests, and identified the effect of each component on the reliability of the balance system. On this basis, we presented a Markov model for the reliability of the balance system, assuming that the data acquisition of a typical flying model should be complete in less than 15 min in order for the balance system to be considered reliable. Simulation of the proposed model with SHARPE software showed that if we reduced the time of the experiments from 30 min to 15 min, the reliability of the balance system improved by about 30%. In addition, the cost of the experiments in the wind tunnel was reduced by 20%-30%.

Key Words: Reliability, Markov model, wind tunnel, balance system, strain gage

1. Introduction

Wind tunnel systems have been used by aerospace system designers for the past century. The survey of a flying object's motion, such as that of aircraft or missiles in the atmosphere, is a very complicated subject, and the mathematics involved is highly intractable (Soltani and Davari, 2004). Therefore, in most cases, the motion of flying objects is investigated using wind tunnels and relevant devices to measure the applied forces and moments. Understanding the nature of these forces and moments is very important in design optimization of

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missiles, aircraft, automobiles, and other moving objects having relative velocity with respect to the air (Harper and Pope, 1999).

Hence, a device that can precisely measure forces and moments in 3 dimensions is of prime importance in aerodynamics. One of the most efficient methods to precisely measure these parameters is the balance system (Hassani Ahangar et al., 2006), since reliability plays a very important role in the engineering management of military systems. Thus, reliability-based systems in design and construction of engineering components will greatly enhance the performance of such systems (Hansson et al., 2002). Although the reliability discussion has been involved in the design and construction of different systems, the expansion of technology and the complexity of tools have made it one of the most advanced technologies in strategic and dynamic industries in recent decades (Hassani Ahangar and Haghiri, 2006).

Generally, 2 methods of prediction and estimation are used for evaluation of reliability. In the first method, system reliability is predicted by using mathematical modeling, constitutive element information, and the performance of the system. In the second method, system reliability is estimated by using the results of life experiments and failure rate modeling (Laprie, 1992). In this article, reliability parameters of the balance are calculated by using the prediction method through mathematical modeling and constitutive element information (Hassani Ahangar et al., 2007).

2. Balance equipment

Balance equipment is a device that measures the required forces and moments of the model in the wind tunnel. Balance devices are divided into 2 categories, internal and external (Hassani Ahangar and Haghiri, 2006). In this article, the internal balance is modeled and evaluated. Figure 1 shows a typical static 6-component balance. Balance measurement systems are dominated by the law governing the strain gage systems. Strain gage is an electric resistance made of metal or a semiconductor, for which change in its length will cause changes in its resistance. The relation between resistance and strain was investigated by using the factors affecting the resistance. Strain gages were glued in the proper position and direction, such as a Wheatstone bridge, upon surfaces under strain and stress (Carlson and Gisser, 1990; Hassani Ahangar et al., 2005).

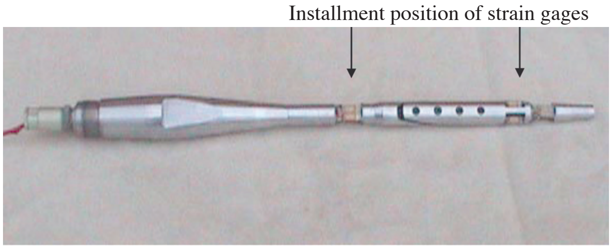


Figure 1. A 6-component static balance.

The top and left views of the strain gage positions are shown in Figure 2A. The component shown is under flexural moment, and 2 strain gages, R_1 and R_4, are shown. The strain gages are under tensile forces. The other 2 strain gages shown on the right of Figure 2A, R_2 and R_3, are under compression stresses. The left side of Figure 2B shows the top view of the real strain gage installed on the balance, and the right side shows the equivalent electrical bridge of the component.

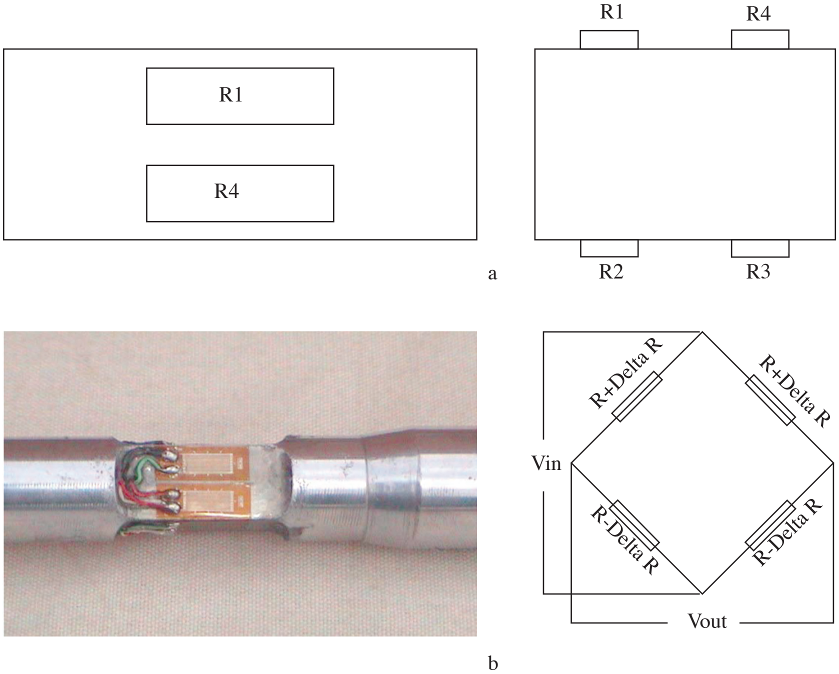


Figure 2. Placement of strain gages on a balance surface.

By supplying power (DC) to the system, the bridge was initially balanced. After exerting force to the system, the strain and stress occurred and the amount of the strain gage's resistance changed. This variation of resistance appeared in the output bridge as a voltage change. By using this voltage variation, the amount of existing strain and stress of the surface was obtained (Edwards, 2000; Soltani and Davari, 2004).

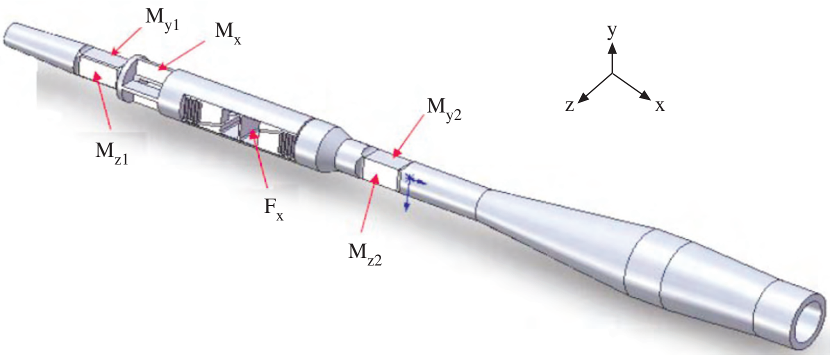
A balance device is able to separate 3 force components (Fx, Fy, Fz) and 3 moment components (Mx, My, Mz) in the defined scope (Hassani Ahangar and Haghiri, 2006). Thus, a combination of 6 electrical bridges is needed, as shown in Figures 2 and 3A. The equivalent circuit of this balance is presented in Figure 3B.

Balance is used to measure force and moment levels. The true mechanism is such that when a force and a moment are applied to a model connected to the balance, some elastic deformations, which are dependent on the force or moment, are created in different parts of the balance. These deformations are measured using a strain gage. Errors that appear in a balance are divided into 4 groups (Hassani Ahangar et al., 2005):

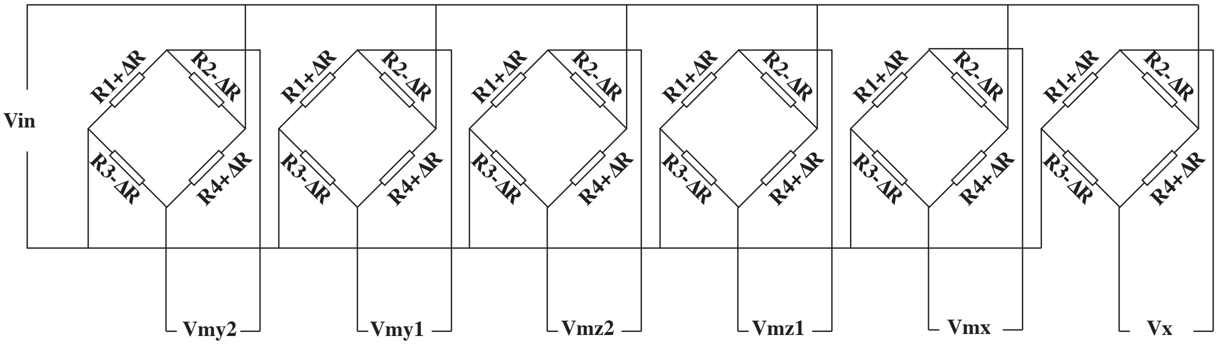
1. Errors that develop because of balance structure,
2. Errors that are created because of strain gages,
3. Errors of human factor, and
4. Errors of environmental effects.

2.1. Structural errors

A balance must be designed in such a way that the deformations developed by a force or moment are localized to allow the forces and moments to be measured independently (OMG, 1999; Edwards, 2000). However, in practice, the interaction among the forces and moments creates some nonlinearity and some errors during the calibration process. Therefore, the balance structure and the strain gage positions must be defined such that



a. The position of bridges on a 6-component balance.



b. The circuit of bridges of a 6-component balance.

Figure 3. The 6-component balance: A) position of bridges, B) circuit of bridges.

the responses of the balance to the forces and moments become linear and are without interactions between the applied loads. Another point to mention is that the temperature variations always account for undesirable changes in the structure.

2.2. Errors created in strain gages

A strain gage is a resistance for which the value changes because of changes in its length. Errors that appear in strain gages fall within 4 categories:

1. The sensor-inherent error,
2. Error in the glue used to fit the strain gage into the structure,
3. Error in the power supply that is connected to the strain gage bridges, and
4. Error in the socket and the transmission lines of strain gage heads.

These errors can be mitigated by using strain gage and other accurate and highly reliable instruments (OMG, 1999; Liberato et al., 2000).

2.3. Human factor errors

Human factors can be used in any system. The use of the balance in the wind tunnel to obtain data is mostly dependent on the operator's physical and mental status, which must be considered in the reliability assessment. Human effects must be directly taken into account, and in this article, this effect is considered as a constant amount and is added to the other errors (Kandasamy et al., 2003; Hassani Ahangar and Haghiri, 2006).

2.4. Environmental effects

An environmental error is a type of error that affects the atmospheric conditions permanently. These parameters include environmental pressure, temperature, humidity, noise, and radiation. For instance, temperature variation is a kind of error source that causes undesirable deformation in the structure. The length of time will also affect the subsystem characteristics, and this is a very important and effective factor on balance reliability. It is obvious that the above-mentioned factors do not add or subtract any factor from the relations, but do affect the system performance in the environment, and this will increase or decrease the reliability and capability of the system (Avizienis and Laprie, 1986; Hassani Ahangar and Haghiri, 2006).

3. Balance system's modeling reliability point of view

As was mentioned previously, a balance system consists of many different parts. Failure of any part will result in the failure of the whole system. Therefore, the whole system's reliability is dependent on each part's reliability. The considered balance here was a 6-component static balance. It consisted of 6 strain gage bridges, which were appropriately fed with a permanent 6-V power supply (Hassani Ahangar and Haghiri, 2006).

As far as the failure mode is concerned, the strain gage installment structure's adhesive materials and transmission lines were in series. Figure 4 shows the diagram of component parts in the case of failure. Strain gage bridges were separated from each other, and due to their failure effects on each other, they were considered parallel; eventually they were in series with the power supply. Figure 5 shows the reliability block diagram (RBD) of a 6-component balance with a power supply of strain gage bridges.

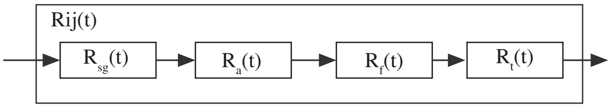


Figure 4. Reliability block diagram R_{ij} (t).

In Figure 4, R_{ij} (t) is the jth strain gage reliability from the$i$th bridge and balance bridge, and R_{sg}(t) is the strain gage reliability. R_a(t) is the adhesive reliability, R_f(t) is the foundational reliability, R_t(t) is the transmission line reliability, R_{su}(t) is the power supply reliability, and R_j(t) is the equivalent jth bridge reliability.

4. Computation of the balance reliability

According to what was presented previously, using parallel and serial component relations along with Figures 4 and 5, the total balance reliability R'(t) and the power supply reliability R_{su} are equal to R(t). Then:

$$R_{ij}(t) = R_{ijsg}(t).R_{ija}(t).R_{ijf}(t).R_{ijt}(t)\forall i = 1,\ldots,6; \forall j = 1,\ldots,4; \tag{1}$$

$$R_i(t) = \prod_{j=1}^{4} R_{ij}(t) \forall i = 1, \ldots, 6; \tag{2}$$

$$R'(t) = 1 - \prod_{i=1}^{6}(1 - R_i(t)); \, and \tag{3}$$

$$R(t) = R'(t) * R_{su}(t). \tag{4}$$

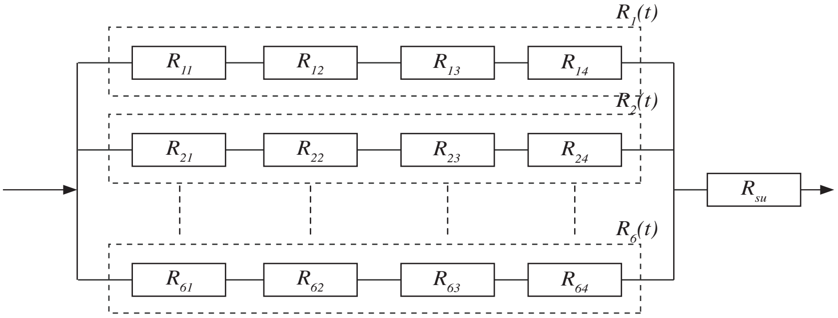


Figure 5. Reliability block diagram of 6-component balance.

5. Balance system Markov model

If λ is considered as the strain gage failure rate and μ as the power supply failure rate, the Markov model of the balance system can be portrayed as in Figure 6 and a different analysis of the reliability system and availability can be presented. Each state in the Markov model system is considered as a regular pair (i, j), i defining the number of flawless bridges and j defining the undefective power supply. First, considering that the whole system and its components are undefective, as in Figure 6, the system is in state (1, 4). Here, the number 1 represents an undefective power supply and number 4 a flawless combination of strain gage bridges. When the system is working, different states will emerge according to the failure of each component, as shown in Figure 6.

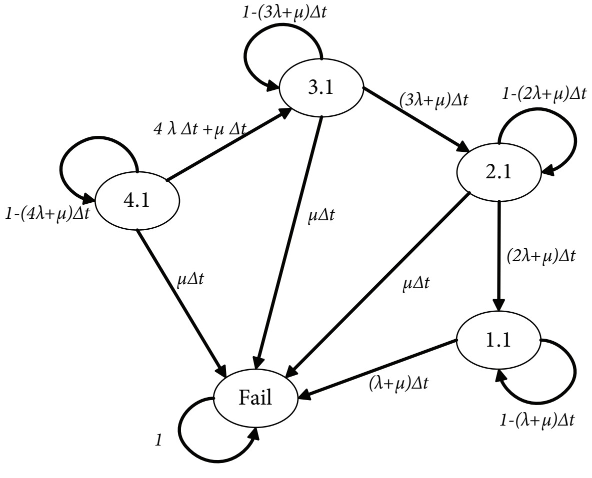


Figure 6. Markov model of the balance.

The rules governing the Markov model in order to obtain balance reliability are as follows:

$$\begin{aligned}
&P_4(t+\Delta t) = (1-(4\lambda+\mu)\Delta t)P_4(t),\\
&P_3(t+\Delta t) = (1-(3\lambda+\mu)\Delta t)P_3(t) + 4\lambda\Delta t P_4(t),\\
&P_2(t+\Delta t) = (1-(2\lambda+\mu)\Delta t)P_2(t) + 3\lambda\Delta t P_3(t),\\
&P_1(t+\Delta t) = (1-(\lambda+\mu)\Delta t)P_1(t) + 2\lambda\Delta t P_2(t),\\
&P_f(t+\Delta t) = \mu\Delta t P_4(t) + \mu\Delta t P_3(t) + \mu\Delta t P_2(t) + (\lambda+\mu)P_1(t).
\end{aligned} \tag{5}$$

According to Eq. (5) and the initial conditions, it can be seen that $P_1(0) = 0$, $P_2(0) = 0$, $P_3(0) = 0$, and $P_4(0) = 1$. The probabilities are in time domain first and are then transformed into s-domain, and then the probability of the system at a specified state is computed (Trivedi, 2002). The probabilities are then converted into time domain. The results are:

$$\begin{aligned}
P_4(t) &= e^{-(4\lambda+\mu)t}\\
P_3(t) &= -4e^{-(4\lambda+\mu)t} + 4e^{-(3\lambda+\mu)t}\\
P_2(t) &= \tfrac{6}{\lambda}e^{-(4\lambda+\mu)t} + \tfrac{6}{\lambda}e^{-(2\lambda+\mu)t} - \tfrac{12}{\lambda}e^{-(3\lambda+\mu)t}\\
P_1(t) &= \tfrac{24}{10\lambda+4\mu}e^{-(\lambda+\mu)t} + \tfrac{24}{10\lambda+4\mu}e^{-(4\lambda+\mu)t} - \tfrac{24}{10\lambda+4\mu}e^{-(2\lambda+\mu)t} - \tfrac{24}{10\lambda+4\mu}e^{-(3\lambda+\mu)t}
\end{aligned}$$

Finally, the system reliability is obtained from the following relation:

$$R(t) = P_1(t) + P_2(t) + P_3(t) + P_4(t). \tag{6}$$

6. Evaluation of balance reliability model

As mentioned earlier, a balance system is composed of a number of components or subsets. In computing the balance reliability, the reliability of strain gage and structure are more important than the other balance components. In the following paragraph, the proper way to obtain these important components is delineated.

7. Reliability of strain gage

In this balance, large EA-series strain gages from Measurement Corporation were used (Edwards, 2000). According to the maximum rate of tension exerted on the strain gages, which is the worst condition that may occur for the balance, the failure rate of the strain gages was investigated using the diagram of strain gage standard duration time, as shown in Figure 7. The results of the assessment are presented in Table 2.

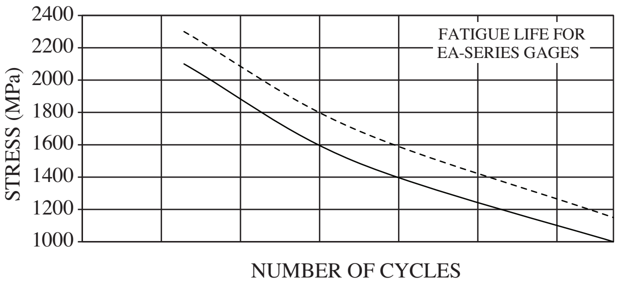


Figure 7. Duration time of strain gage EA-series.

8. Reliability of structure

Since the maximum force exerted on the balance in a critical angle of attack and at a specified Mach number is 450 N, a maximum force of 500 N was considered to have a higher safety factor for the structure, which is an alloy very close to steel ST-4130. In order to obtain the fatigue curve in the vicinity of 300 N $\leq$ force $\leq$500 N, a force was applied to the balance structure using a frequency of 8 Hz and environmental temperature and humidity conditions. The force exertion and repetition are presented in Table 1.

Table 1. Amount of force applied to balance (used to draw fatigue curve).

Force (N)	Tension (σ) (Kip/in^2)	Time duration (cycle)
300	49.8	3,000,000
300	49.8	1,200,000
350	55.98	400,000
350	55.98	150,000
400	63.97	200,000
400	63.97	60,000
450	71.90	40,000
450	71.90	60,000
500	79.96	45,000
500	79.96	30,000

Based on Eq. (7), the bending stress σ of the strain gage location in terms of different forces can be calculated using the following relation:

$$\sigma = \frac{MC}{I}. \tag{7}$$

Here, M is the bending moment and is equal to the force times the distance from the balance tip to the strain gage location. I is the crosssection moment of inertia and C is the center of mass distance to the center of the strain gage location. The results of the calculations using Eq. (7) are presented in Table 1. Figure 8 shows the fatigue diagram of this alloy along with the standard fatigue diagram of ST-4130 (DOD, 1984). The maximum failure rate and structure reliability were computed using Figure 8. The results of the computation are shown in Table 2.

Table 2. Failure rate of balance components.

Title	Balance failure rate, λ , and power supply failure rate, μ (cycle)
Strain gage	2.5×10^{-8}
Structure	10^{-5}
Connector	2.1×10^{-5}
Power supply	6.3×10^{-5}

Mean time to failure for the balance component was computed by substituting the relevant parameters of Table 2 in Eq. (7) and Eqs. (1-4). The results are presented in Table 2.

The diagram of the balance system components' reliability based on the parameters of Table 2 is presented in Figure 9. The diagram was generated with the help of SHARPE software (Carlson and Gisser, 1990).

Table 3. Failure rate of balance.

Title	MTTF (cycle)
A strain gage along with structure and other components	32,232.1
An equivalent bridge	14,438
Balance	8058
Balance and power supply	5344.7

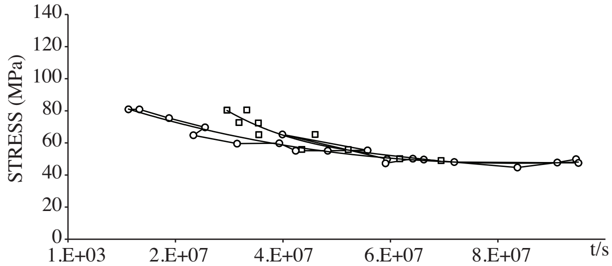


Figure 8. Alloy fatigue diagram and standard fatigue diagram of steel ST-4130.

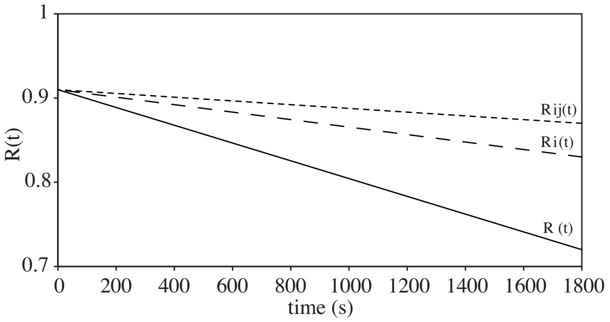


Figure 9. Reliability of strain gage (R_{ij} (t)), strain gage equivalent bridge (R_i (t)), and balance (R(t)).

If the diagram of system reliability is analyzed carefully, it can be seen that the selection of the maximum operation (wind tunnel experiment) time had a considerable effect on the system reliability. That is, if the time of the experiment was more than 1800 s, the system reliability was reduced to 0.7. So great a drop in reliability is not acceptable for the required accuracy of the system. Avoiding this will lead to a reduction in experimentation cost between 20% and 30%. At the same time, it will increase the reliability level of experiment results for relevant industries.

It seems more appropriate to reduce the time of the experiment in each operation in order to maintain the system reliability at an acceptable level. Figure 9 shows that the system reliability was much lower than the reliability of strain gage and the configuration of strain gage bridges. This was due to the low reliability of the power supply, which was in series with the strain gage's bridges. In order to increase the operation time, it is required that a power supply with higher reliability be used, or a different power supply, as a redundant one, be employed.

9. Conclusions

Wind tunnel experimentation is a complicated and time-consuming process. In addition, the high cost and multiple side effects (loud noises) are of significant importance. The process must be performed with proper safety considerations as well as high reliability in order to avoid repetition of costly experiments.

In this paper, a balance structure and its fault sources were investigated and analyzed. The balance was modeled from the reliability point of view and investigated based on the reliability parameters of its components. The performance of the balance was simulated for 30 min. An important noticed result showed that because of the large drop in reliability of force and moment strain gages as time passes, wind tunnel experiment data at the beginning and at the end of the experiment may not be at an acceptable level of reliability. This may cause unsubstantiated analysis of the model and result in financial and human losses. This will have an important effect on the reduction of confidence in wind tunnel-oriented industries and loss of revenue in this respect. For this reason, flying object experiments should be performed as quickly as possible, not taking more than 15 min. This will require good and accurate measuring systems with highly reliable data acquisition.

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