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# EVALUATION OF AERODYNAMIC STABILITY AND UNWANTED VIBRATIONS ON CONTROL SURFACES UNDER EXTREME GUST LOADS

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**Abstract.** The paper evaluates the aerodynamic hindrance caused by gust loads and vibrations produced by the aircraft control surfaces during different oscillated flight regimes. The approach aims to design an automated system in order to predict the unknown and required parameters of aircraft in flight testing phase. A mathematical model of a full-scale civilian Unmanned Ariel Vehicle (UAV) was tested along with its industrial prototype to study and observe the unique characteristics of aircraft. The model was synchronized with the parameters of the industrial prototype, and checked according to the aviation standards. It was then verified using the data acquired through real-time flight-testing at the research base. The geographical coordinates of the research base and the weather data from the previous two years were also obtained and introduced into the automated system. A series of automated flight tests were conducted with and without extreme conditions to analyze the feasibility of the novel approach. The experiments were carried out not only to verify the validity and effectiveness of new purposed system but also the characteristics of aircraft through the new method. The simulated results would be beneficial in considering the accuracy of the new automated system, in contrast with the conventional system. The automated system will give the upper hand to verify the end product accurately and with no life-threatening tasks in challenging circumstances, besides it will also assist to refine the procedures and techniques in pre-production research and manufacturing.

**Key words:** aerodynamic hindrance; gust loads; turbulences; flight dynamic; flight regimes; UAV; static stability; dynamic stability; elevators; flight envelope; test flights; ailerons.

## INTRODUCTION

To ensure flight safety and predict catastrophic dimensions caused by ambiguous feedbacks during flights, aircraft must drift through specific flight test requirements [1]. The key tasks of flight tests are to verify the stability and controllability of an aircraft in different flying modes. The evaluation of the ultimate design of aircraft and certification solely depends on the dynamic and static stability of the aircraft. The automated system will provide research and manufacturing units to verify the given design in order to study the technical feasibility of the aircraft and feedbacks, which will facilitate to alter design parameters or manufacturing tactics used in final assembly.

The atmosphere and the parameters surrounding the aircraft play a vital role in analyzing the stability and performance during a straight flight. These parameters include wind, visibility/ceiling, high-density altitude, turbulence, icing, precipitation, icing, thunderstorms, thermal lift, lightning, and other extreme atmospheric parameters, which are all-weather phenomena that cause or contribute to aviation accidents [2, 3]. Along with stability, some minor damages also question the quality of work and procedures used in the manufacturing.

During the lateral movement and the dynamic motion, the meteorological parameters such as gust loads on the aircraft's components could produce unwanted vibrations and noises, resulting in data glitches for the onboard system, creating hoax output against the required parameters for the flight. Besides this, the generated disturbances or turbulences may cause aircraft to move out of the straight path and continue to fly in an unstable mode. This may lead to either a catastrophe, undesirable incidents or some structure damage to the aircraft.

For the newly build prototype or type-rated aircraft, it's almost impossible and hard to find some unknown parameters and characteristics of aerodynamics stability of the aircraft without a maiden flight test. In addition, to determine the unknown figures, the flight test crew must stake their lives in order to acquire some data which maybe sometimes not so much accurate because of approximation and human error.

The gust load, atmospheric gust or turbulence is the most common extreme meteorological parameter encountered by aircraft on their usual flights [2, 4]. The gust load is defined as a sudden short blast of wind for little time, which may cause an aircraft to deflect from its original flight path. It's the mixed components of aerodynamic forces acting on the aircraft body [5]. It means that the total velocity of wind acting on the aircraft is the sum of the vector components of air's velocity acting on the aircraft, which can be expressed as follows:

$$V_{gust} = \begin{bmatrix} \vdots \\ u_{gust_j} \\ v_{gust_j} \\ w_{gust_j} \\ \vdots \end{bmatrix}. \tag{1}$$

Which further could be explained in terms of linear vector:

$$V_{gust} = ui + vj + wk. \tag{2}$$

Other than the velocity of air, the gust load factor $n$ also plays an important role in assuming the characteristics of aircraft, which can be written as [4]:

$$n = L/W = 1 \pm \Delta n. \tag{3}$$

Where W is the weight of aircraft, L is the lift force exerted on the aircraft and $\Delta n$ change in acceleration by the gust load. The gust load factor decides the performance of aircraft and its structural strength to understand the aircraft limits under atmospheric loads, which may create unwanted aero-elasticity and flutter.

To further understand this phenomenon, a flight envelop of aircraft must be made after some series of flight tests which uses *V–n* diagram (see fig. 1), so the aviators and pilots must fly within the maneuverable and aerodynamically control regimes [6]. Any activity outside these boundaries considered as unsafe or hazardous.

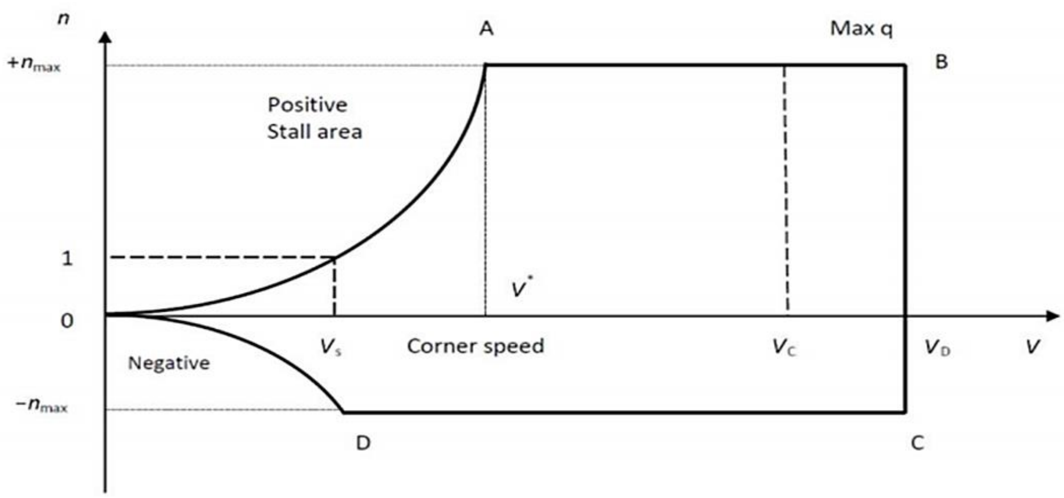



**Fig. 1.** A typical flight envelope expressed using V-n diagram

In order to get that data, the maiden test flights must be carried out to understand the stability and aerodynamic behavior of the aircraft. Due to the processes involve, it's not only expensive but also unsafe and technically not quite accurate procedure to get all the data required to make flight envelop of required aircraft.

In the following case, a civilian UAV (see fig. 2) for a fully functional automated flight test was used. The mathematical model of aircraft was used to create the algorithms for the automated system and automated flight test. Numeric computing was introduced as the crucial element to create a real-life environment to understand the characteristics of aircraft, without flying the original prototype and involvement of a heavy crew of flight test personals. The maiden flights with low intensity maneuvers were made and data acquired was used to refine the mathematical model for the further extreme maneuvers testing. Those maiden flights were served to determine the parameters of aerodynamic and moment forces. Which were then matched with the parameter within the model [7]. Some further stability tests were conducted to validate the model for the automated system.


**Fig. 2.** Designated UAV "Jupiter-2"

The experiment was regulated to determine the aerodynamic stability of aircraft with variable and hazardous gust load, which may cause unknown hindrance and damage to aircraft flying out of the bound. The same result would be beneficial for the flight test engineers and scientists in determining the "flight envelope" and other flying and technical characteristics of aircraft without involvement in critical situations and even before any production phase.

**MATHEMATICAL MODEL AND AXIS OF MOVEMENTS**

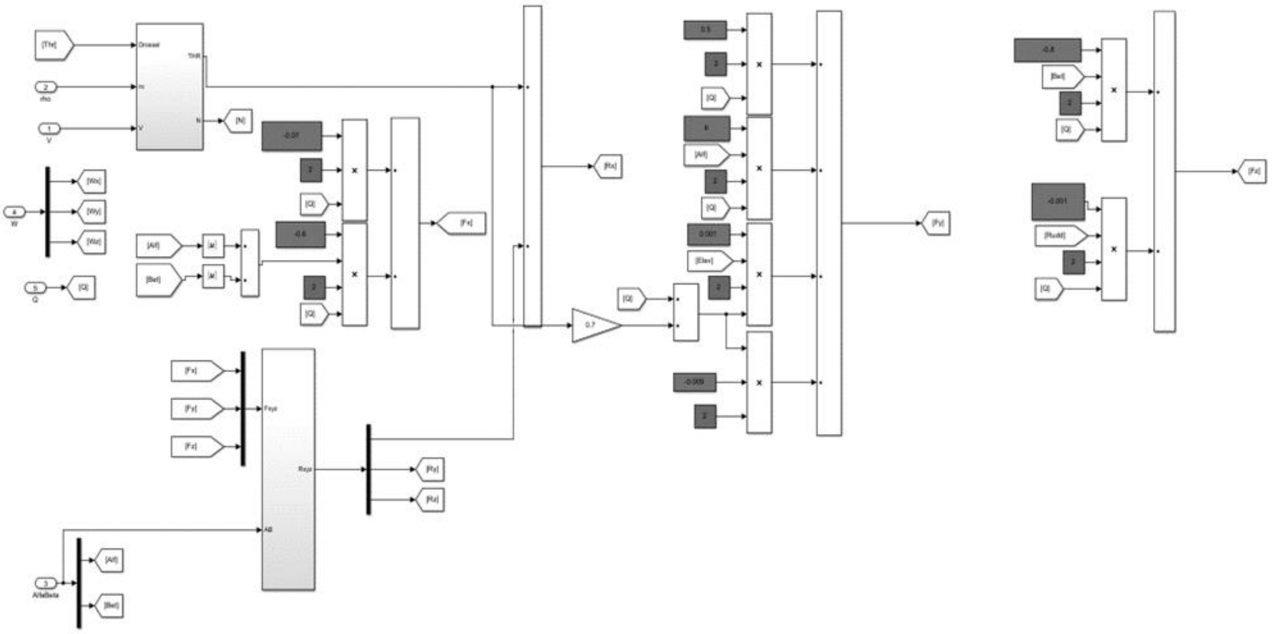
The aircraft follows strict rules of the equations of motion to remain stable and to get airborne [8, 9]. This set of equations makes up a mathematical model that defines a particular aircraft. Here, the necessary parameters of the UAV (see table 1) to refine the mathematical model of movement along a smooth trajectory were considered, excluding weak conditions, including noise and other distortions. In addition to this method, the separation of calculations greatly aided in adjusting the model to match the UAV's parameters in real-time [7].

Table 1

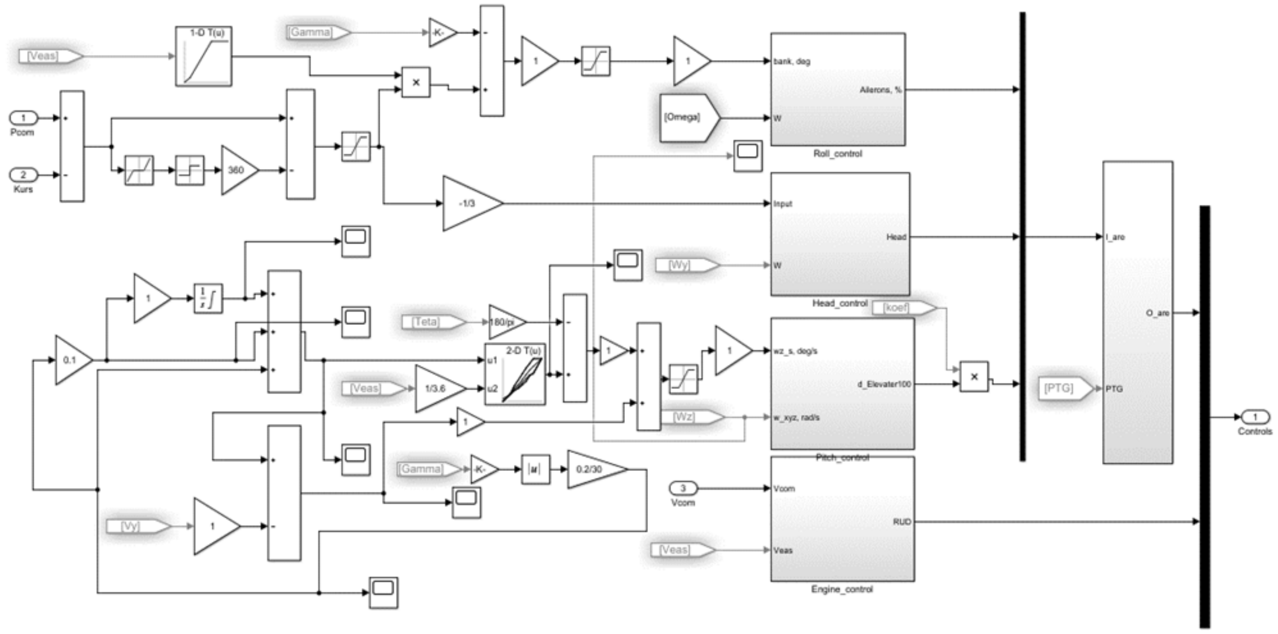
**Jupiter-2 Specifications**

| *Characteristics* | *Values* |
|---|---|
| Maximum speed | 150 km/h |
| Cruising speed | 125 km/h |
| Range | 1000 km |
| Service ceiling | 3000 m |
| Take off | 300 m |
| MTOW | 100 kg |
| Length | 4 m |
| Height | 1 m |
| Wingspan | 8 m |

The mathematical model describes the components of the forces, movements, and aircraft position relative to the fixed coordinate systems (see fig. 3). The approach of representing the exact aircraft orientation used the Euler angles to refine and obtain the exact equation as required [9].



*a*




*b*

**Fig. 3.** Model of UAV dynamics:
*a – fragment of aerodynamic block; b – flight control system block*

To understand the mathematical model, consider the rate of change of momentum $\left(\frac{dp}{dt}\right)$ acting on flying aircraft on all axes, and take Z-axis as the vertical axis for the calculations.

$$\left(\frac{dp}{dt}\right)_x = m_{air}\Delta V_{air} + Rx\,\mathrm{Cos}\psi\,\mathrm{Cos}\vartheta + Ry\,\mathrm{Sin}\psi + Rz\,\mathrm{Sin}\,\vartheta\,\mathrm{Cos}\varphi;$$

$$\left(\frac{dp}{dt}\right)_y = Rx\mathrm{Sin}\psi - Ry\mathrm{Cos}\psi\,\mathrm{Cos}\varphi + Rz\mathrm{Sin}\psi \tag{4}$$

$$\left(\frac{dp}{dt}\right)_z = Rx\mathrm{Sin}\,\vartheta + Rz\mathrm{Cos}\varphi\mathrm{Cos}\vartheta.$$

Whereas reaction forces reacting on the aircraft are as follows:

$$R_x = qS\left(C_{x0} + C_x^{\psi}\psi\right);$$

$$R_y = qS\left(C_y^{\vartheta}\vartheta + C_y^{\delta r}\delta_r\right); \tag{5}$$

$$R_z = qS\left(\left(C_{z0} + C_z^{\psi}\psi\right); + \left(\delta_e C_z^{\delta e} + C_z^{stab}\right)\left(q + TK_{tq}\right)\right).$$

The model further uses the basic concept of the Euler Angles for the roll, pith and yaw movements, which are defined as [10]:

$$\hat{a} : \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix}. \tag{6}$$

After substitutions of values and constants, the ultimate values for the angular velocities are defined as:

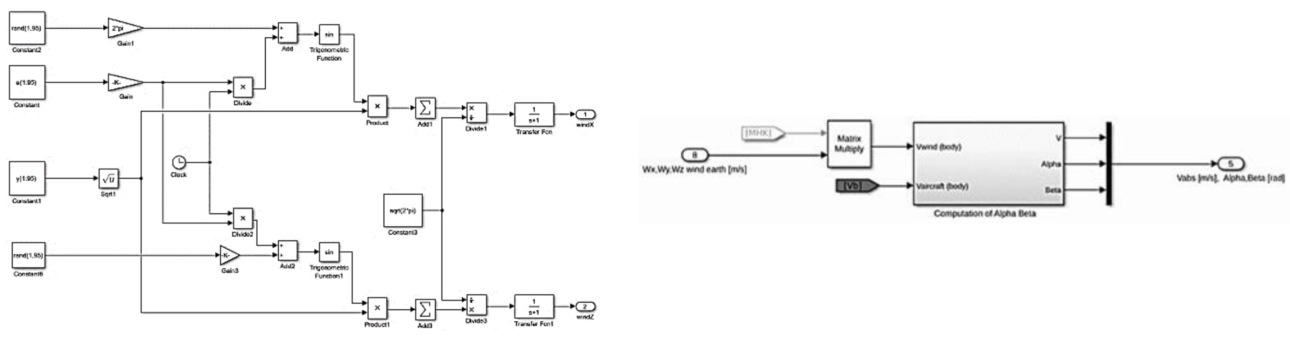
$$\begin{pmatrix} \omega_1^b \\ \omega_2^b \\ \omega_3^b \end{pmatrix} = \begin{bmatrix} 1 & 0 & -\sin\theta \\ 0 & \cos\varphi & \cos\theta\sin\varphi \\ 0 & -\sin\varphi & \cos\theta\cos\varphi \end{bmatrix} \begin{pmatrix} \dot{\varphi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} \tag{7}$$

The implementation of the rotational matrices in Euler angles defines the movements of the aircraft reference with the global coordinates, which were reconstructed using the numerical analyses methods.

## ALGORITHMS AND BASIC METEOROLOGICAL PARAMETERS

Numerical analyses methods were used to break down the mathematical model into the sub parts in order to understand the basic principles required for the approach. Algorithms were used to define the problem in the more sophisticated way.

This approach is based on a deep analysis of the aircraft dynamics during atmospheric disturbances to evaluate the situation and provide effective resolutions, which could be useful in determining the outer boundaries of the flight envelope. Illustration of fig. 4, *a*, shows the typical algorithm of wind circulation in that area, whereas fig. 4, *b* shows the block diagram wind model and other matrices to obtain and implement the meteorological data within the system boundary.



*a* *b*

**Fig. 4.** Illustration of atmospheric mathematical models within the system:
*a – block diagram of wind circulation; b – block diagram of implementation in the systems*

## TESTS UNDER IDEAL AND EXTREME CONDITIONS

The identification of the parameters was carried out by recording the performed control surfaces (rudder, elevator) shifts and rectilinear flight modes with variable aircraft velocity. In ideal conditions, the components of wind or gust load were turned off or set to the zero to observe the roll, pitch a yaw movement of aircraft with no roughness or disturbance.

A global coordinate system model was also added to the automated system along with the atmospheric elements. Weather data were collected for two years from the same region (the region for flight tests). A tool was introduced to simulate an almost realistic aircraft flight mode model with the very narrow margin of errors.

The Russian standards for aviation and aerospace were changed to international standards for aviation and aerospace. Thus the *Y* and *Z* components were interchanged with each other and minor coding was involved to translate the old coordinate system into the new coordinate system. The vertical component, which is *Y*-component of gust load, is used in real or extreme conditions to determine the loss of control of aircraft beyond the critical angle of attack $\alpha > 15°$. *Z*-component is enough to create slide slip and directional instability, causing aircraft to enter Dutch-roll to get back valuable feedbacks for the estimation of the maneuverability.

– *Under Ideal Conditions:* For the experiment in ideal conditions, as already explained, the components of gust loads were set to zero to see the maneuverability of aircraft with no distorted air. For the experiment, the optimal and initial velocity was set to $u$ = 120 Km/h at longitudinal axis *X*. Components *v* and *w* were kept 0 Km/h to give a flight straight path.

During the experiments, different dynamic flight modes were tested under some given conditions, circumstances and pilot induced oscillations. To validate the stability, all the dynamic modes were simulated artificially using the data from flight controls. The output result includes the systematic values of stability and other aerodynamic coefficients.

– *Under Real Conditions:* The only difference between real conditions and ideal conditions is the component values of the gust load. In ideal condition there is no or almost zero gust load whereas in real conditions gust load has the value of: $V_{gust}$ = 70 Km/h. The values for the local weather was introduced only in transverse and longitudinal vector in the first experiment and gust values in the remaining vector. Experiment was carried out with the different schemes and configurations.

In contrast with ideal conditions, the real conditions used discrete gust loads, under its given shape and velocity [11]. The shape follows gust velocity and height, which can be described as:

$$U = \frac{U_{ds}}{2}\left[1 - \cos\left(\frac{\pi s}{H}\right)\right] \qquad (8)$$

Where $s$ is distance penetrated; $H$ is the gust gradient; $U_{ds}$ is the design velocity of the continues gust, which can be further described as follows:

$$U_{dS} = U_{ref} F_g \left(\frac{H}{350}\right)^{\frac{1}{6}} \qquad (9)$$

Where $F_g$ is flight profile alleviation factor and $U_{ref}$ is reference gust velocity, which is ≈ 40 Km/h.

## RESULTS

In the first run, simulation was run for the several seconds with almost no or zero loads in the straight path.

Table 2

**Initial Conditions**

| *Parameters* | | *Initial values* |
|---|---|---|
| Altitude | H (m) | 1000 |
| Initial velocity | u (m/s) | ~ 40 |
| Angle of attack | α (rad) | $-90 < \alpha < 90$ |
| Slip angle | β (rad) | 0 (constant) |
| Roll angle | φ (rad) | $-180 < \varphi < 180$ |

The movements of aircraft were recorded and followed to compile the final statics about the characteristics of the aircraft. The simulation was again run for several times with some extreme conditions to check output results, performance and the response of the aircraft.

Fig. 5 shows the rapid response of the aircraft (UAV) against the shift position of elevators and altitude of the aircraft and minor change in it. Whereas fig. 6 shows the only minor change in the altitude as the position of ailerons changes. This occurs due to the change in the angular velocities and linear velocity regarding the straight path.

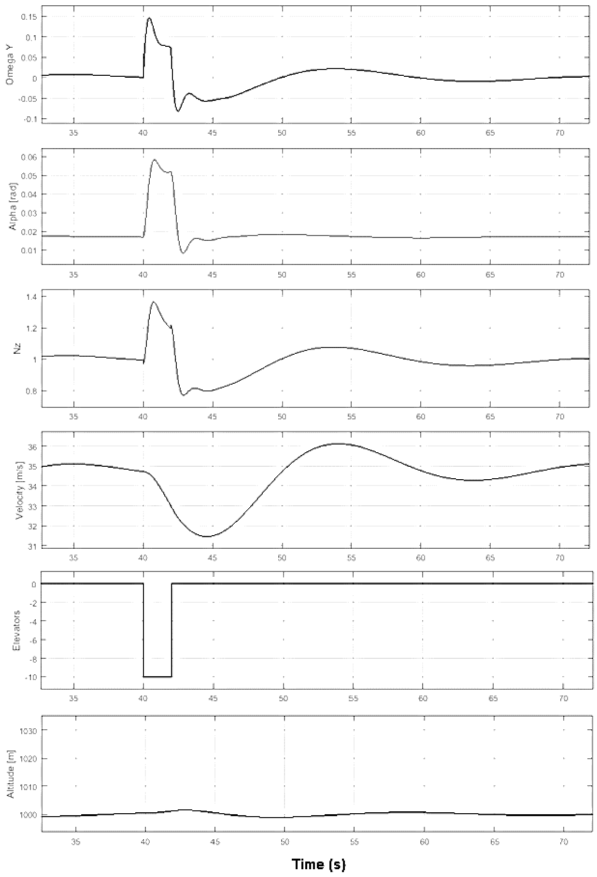



**Fig. 5.** Elevator response graph

The position of elevator defines the altitude of a flying aircraft. The intensity of its position creates movement, which results in the altitude. Fig. 7 shows the response of vibration occurred through the intense wind, which resulted in the slightly higher rate of change of altitude $\Delta H \approx \pm 10$ m. The movement of aircraft back to the original position defines its characteristics of dynamic stability.

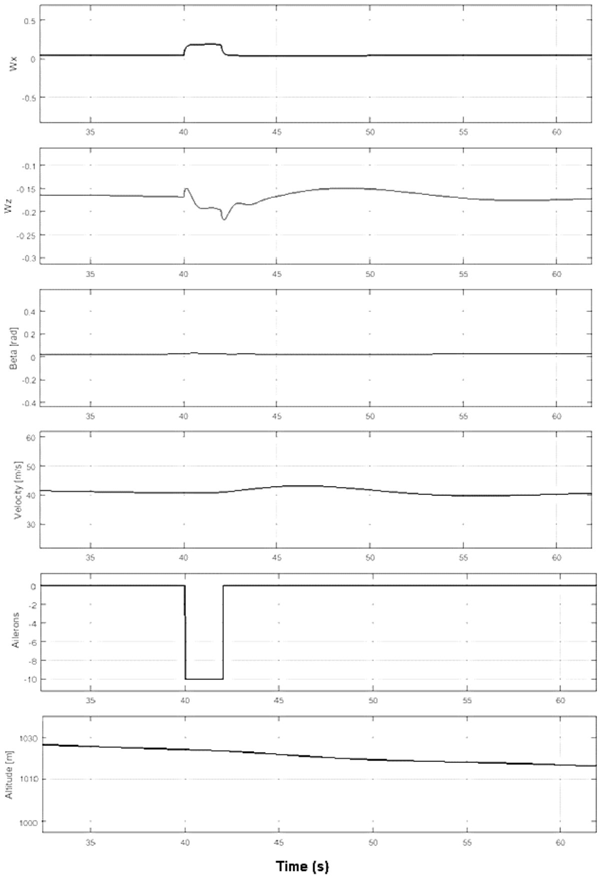



**Fig. 6.** Aileron response graph

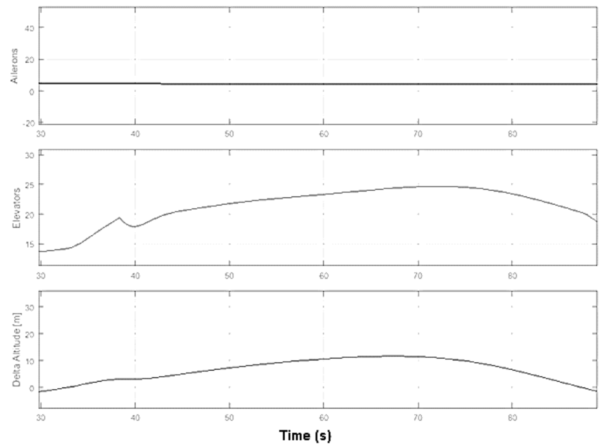



**Fig. 7.** Out of phase movement due to wind circulations

The aircraft was allowed to fly under the same conditions to study the response of elevator position by the pilot against the stability and wind circulations on the aircraft. The fig. 8 and 9 show the instability occurred using the forced feedback on the control surfaces. The pivot point on horizontal stabilizer of aircraft allows it to create the moment forces along that point, which aids in the pitch movement of the aircraft. The position of the elevators themselves define the angle of rotation, but forced input may not only entitle the aircraft malfunctioned but also may cause the catastrophe as the result of structural damage due to inappropriate aerodynamic forces acting on it.

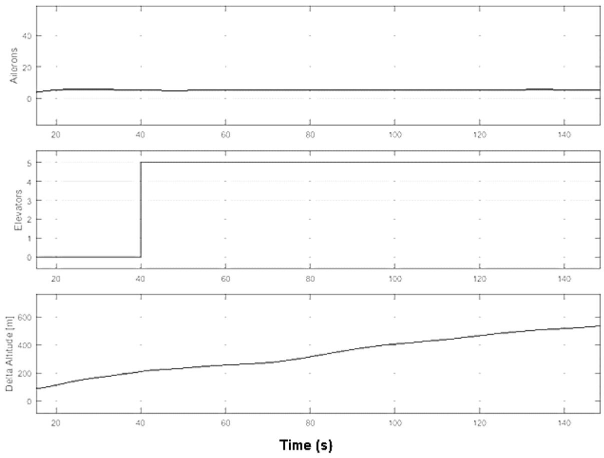



**Fig. 8.** Forced input by the pilot

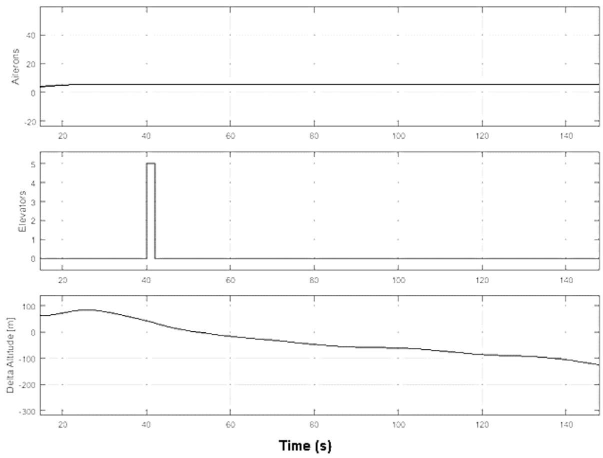



**Fig. 9.** Forced stability control by the pilot under extreme conditions

The vibrations on the control surfaced and their positions must be aligned to allow the aircraft to pass through the high-intensity wind turbulence or disturbance like gust loads and other ambiguities in the atmosphere. Trim tabs at the end of control surfaces need to be adjusted to get desired result. The fig. 10 shows the desired position of the elevators in the intense wind gust and its constant height using the trim tabs in the straight flight.

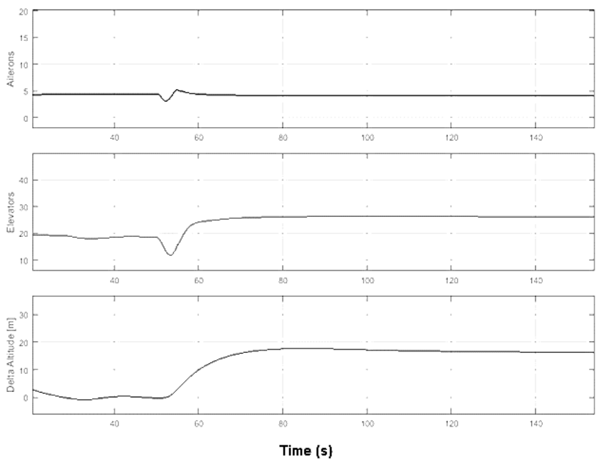



**Fig. 10.** Gust loads on the control surfaces and automated stability response

## CONCLUSION

This approach was used to identify the aerodynamic characteristics and stability of the aircraft in extreme atmospheric conditions. Which may lead to automation of the design validation and verification without the involvement of life-threatening flight tests and expensive production. The results will be useful in studying and analyzing the final design and production methods, which must be applied before the flight test. The results show the limits for the flight envelop and the feasibility of the aircraft. Hence, the automated system proved to be valid and valuable. The approach showed the worth of the design and flows, which can be altered and refined to get smooth product.

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## МЕТАДАННЫЕ

**Название:** Оценка аэродинамической устойчивости и нежелательных вибраций на поверхностях управления при экстремальных порывистых нагрузках.

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**Аннотация:** Оцениваются аэродинамические помехи, вызываемые порывными нагрузками и вибрациями, создаваемыми рулевыми поверхностями самолета при различных колебательных режимах полета. Подход направлен на создание автоматизированной системы для прогнозирования неизвестных и требуемых параметров самолета на этапе летных испытаний. Математическая модель полномасштабного гражданского беспилотного транспортного средства (БПЛА) была испытана вместе с его промышленным прототипом для изучения и наблюдения уникальных характеристик самолета. Модель была синхронизирована с параметрами промышленного прототипа и проверена на соответствие авиационным стандартам. Затем она была проверена с использованием данных, полученных в ходе летных испытаний в исследовательской базе в режиме реального времени. Также были получены и введены в автоматизированную систему географические координаты исследовательской базы и данные о погоде за предыдущие два года. Для анализа осуществимости нового подхода была проведена серия автоматизированных летных испытаний в экстремальных условиях и без них. Эксперименты проводились не только для проверки достоверности и эффективности новой предполагаемой системы, но также для проверки характеристик самолета с помощью нового метода. Смоделированный результат будет полезен при рассмотрении точности новой автоматизированной системы в отличие от традиционной системы. Автоматизированная система даст преимущество для точной проверки конечного продукта и без выполнения опасных для жизни задач в сложных условиях. Кроме того, она также поможет усовершенствовать процедуры и методы при предпроизводственном повторном поиске и производстве.

**Ключевые слова:** аэродинамическое препятствие; порывистые нагрузки; турбулентность; динамика полета; режимы полета; БПЛА; статическая устойчивость; динамическая устойчивость; руль высоты; конверт полета; летные испытания; элероны.

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