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Minimization of the absolute altitude of a low-flying vehicle due to the desire to smoothly bend around the low-frequency components of the sea waves ordinate

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Abstract: The method for minimizing the altitude of a low-flying vehicle moving near the disturbed sea surface is proposed. The altitude is minimized due to the desire to go around the low-frequency components of sea waves, primarily due to the natural property of self-stabilization inherent in non-displacement vessels and wing in ground effect vehicles (WIGs). It is possible to increase the efficiency of minimizing the altitude using the elevator and flaps. It is shown in the work that this control method is quite effective for small maneuverable vehicles at a see wave intensity score above 4 points. In relation to WIGs, this method of movement allows to save fuel by increasing the aerodynamic quality of vehicles with the decrease in altitude.

Keywords: low-altitude vehicle, minimization of average altitude, optimization of flight path, vertical maneuvering, sea waves.

1. INTRODUCTION

Driving at low altitude can give low-flying vehicles advantages in solving some problems. For example, when using the ground effect, reducing the altitude increases the aerodynamic quality of the vehicle, thereby increasing its carrying capacity. The disadvantage of driving at extremely low altitude is the high risk of collision with other objects or uneven ground surfaces. The body of all types of marine low-flying vehicles is capable of withstanding water contact at high speed.

Fig. 1. Wing in ground effect vehicle «Chayka»

It was shown in (Knyazhsky, A. Yu., et. al., 2017 a, b) that, using smooth lateral manoeuvring, it is possible to accurately plot a trajectory over the troughs of the low-frequency component of sea waves. The high-frequency component is slightly squeezed by an air cushion, reducing the need for accounting. The ordinate spectrum of sea waves, which is under the trajectory of the vehicle, tending to move over the troughs of sea waves, is lower-frequency than the spectrum of the ordinates of sea waves under the vehicle, moving rectilinearly. Due to which, as a result of lateral manoeuvring, the region of intersection of the ordinate spectrum of sea waves and the frequency spectrum of vertical manoeuvring of the aircraft increases. The increase in the intersection of the spectra means that the low-flying vehicle can more accurately go around the ordinate of sea waves, trying to maintain a given safe distance to it. In this paper, we study the possibility of minimizing the altitude of a low-flying vehicle only due to the tendency to go around the ordinate of sea waves with the help of vertical manoeuvring. The task of joint use of vertical and horizontal manoeuvres to optimize the 3D trajectory is the direction of further investigation.

The task of minimizing the absolute altitude can be represented by the task of stabilizing a given true geometric altitude h of the vehicle relative to the ordinate of sea waves, mainly using its natural property of self-stabilization due to air cushion. Also, to increase the manoeuvrability of the vehicle and the quality of stabilization, it is allowed to use the elevator and flaps.

Up to date, the altitude of low-flying vehicles near the sea surface may be decreased only due to changes in their design and mode of flight. The novelty of this work lies in the proposal to minimize the altitude due to the desire to lay a path mainly over the troughs of sea waves. The features of low-altitude movement near the sea surface, which must be taken into account when laying the trajectory, are described in

(Abdul Ghafoor, et. al., 2015; Abdul Ghafoor, 2015; Michael Halloran and Sean O'Meara, 1999; Lukomsky Ju.A., Chugunov VS, 1988; Nebylov, AV, et. al., 2000; Nebylov AV, Wilson P, 2002; Yun Liang, et. al., 2010). An analysis of the geometric characteristics of sea waves and the maneuvering characteristics of some modern small and medium low-flying vehicles showed the relevance of a deeper study of the possibility of striving to lay their trajectory over the low-periodic components of sea waves. Of particular importance for solving these problems is the self-stabilization of the ekranoplane. The principles of constructing the measuring equipment that allows with sufficient accuracy to evaluate the parameters of the vehicle movement under conditions of sea waves are described in (Nebylov A.V. ed., 2013; Nebylov A., Watson J., 2016; Nebylov A.V., Wilson P., 2002). In the simplest case, one can measure the altitude with a two-channel altimeter that integrates the readings of location altimeters and vertical accelerometers. Features, properties and methods of modeling sea waves are described in the book (Lukomsky Ju.A., Chugunov V.S., 1988). It is shown here that sea waves have quite powerful low-frequency components.

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For laying the trajectory mainly over the hollows of the waves, it is necessary to perform almost continuous maneuvers, causing overload of the vehicle. If there are people on board the vehicle, it is necessary to use anti-loading suits. Ways to combat overload and their effect on the human body are described in (Gorkova M.V., 2017; Skrjabin E. F., Skrjabin O.E., 2014; Staroverov N.E., 2008, Staroverov N.E., 2017; Yun Liang, Bliault Alan, Doo Johnny, 2010). During a long flight in the wave envelope mode, the crew of the vehicle should be in anti-loading suits.

2. MODELING

Using the MATLAB-Simulink medium, the motion of a low-flying vehicle under conditions of irregular sea waves was simulated. As a result of the simulation, the trajectories were determined in the mode of minimizing altitude at any intensity of sea waves. After that, the average decrease in the absolute altitude was estimated due to the tendency to vertically bend around the ordinate of sea waves. The modelling did not take into account the influence of wind. At the initial stage of the study, this assumption is acceptable, since the purpose of the article is not to evaluate the effectiveness of minimizing the absolute altitude of a low-flying vehicle under real conditions of movement, but to show the possibility of significantly reducing the absolute altitude by going around the ordinates of sea waves mainly using the natural property of self-stabilization of a low-flying vehicle. Taking into account the influence of wind disturbances is a further area of research.

Sea waves were simulated using a fractional rational approximation of the spectrum of irregular sea waves. A polynomial with coefficients in the denominator up to the third order was taken as the transfer function of the low-flying vehicles. This model is acceptable because nonlinear effects in the formation of wind sea waves begin to act only with strong storm waves, the score of which exceeds 6. The transport vehicles considered in this article are not used at such a strong storm sea. Some researchers consider nonlinear effects to be more significant even with a lower degree of excitement, but practically do not describe in detail the physics and mathematics of these effects, which complicates the modelling. Their results are based on statistical processing of experimental data, which cannot be comprehensive and reflect the current properties of a general non-stationary random field.

The reaction of low-flying vehicles, striving to maintain a constant true geometric altitude, to a change in the ordinate of sea waves has a certain delay. It is possible to reduce the delay by starting to perform vertical manoeuvres in advance, evaluating the values of the wave ordinate at a certain distance r in front of the vehicle. For this, the radiation pattern of the radio altimeter must be directed at a certain angle. The distance r depends on the speed of the vehicles relative to the sea surface.

In radiolocation, these issues were resolved back in the 60s when trying to organize the stabilization of a ship by the principle of combined control by error and disturbance. Indignation - the incident wave was not just predicted for a dozen seconds, but was directly measured by radar with a beam tilted forward. Naturally, such a radar device was well stabilized in order to avoid the influence of pitching on the readings of the indicated incident wave sensor. The stabilizer is based on a combination of inertial and position sensors.

Let us assume that for a low-flying vehicle moving at sea disturbance of certain intensity, the average reaction delay of the vehicle within a given time interval is known. Knowing the ground speed of the vehicle, it is possible to determine the distance *r*, by means of which the sea surface ordinate should be estimated in order to minimize the control error created by the vehicle reaction delay. The sum of the sea surface ordinate ahead on course by means of the distance *r* and the true given geometric altitude h_{giv} is called the desired absolute altitude of the vehicle through a period of time equal to the vehicle reaction delay. The vector direction from the vehicle current absolute altitude to the desired absolute altitude by means of the distance *r* is called the desired motion inclination. In order for the low-altitude vehicle to maintain a true given geometric altitude, it is proposed to continuously deflect the elevator by an angle that provides the desired path inclination. The proposed method of the true geometric altitude stabilization is not optimal by the criterion of the minimum control error, since it is possible to increase the vertical manoeuvre ability of the low-altitude vehicle by setting a greater elevator angle and gradually reducing it by the completion of the manoeuvre. This method improving is a further challenge.

To assess the potential of altitude minimization using the proposed method, modelling and simulation was performed in the Simulink environment. The developed model can be presented in the form of four large units: simulation of sea disturbance, simulation of the measuring and control system of the low-altitude vehicle (LAV), simulation of the LAV dynamic motion, evaluation of the altitude minimization effectiveness. An enlarged block diagram of the simulation system for the motion of the low-altitude vehicle seeking to round the low-frequency components of the sea disturbance is shown in Fig. 2.

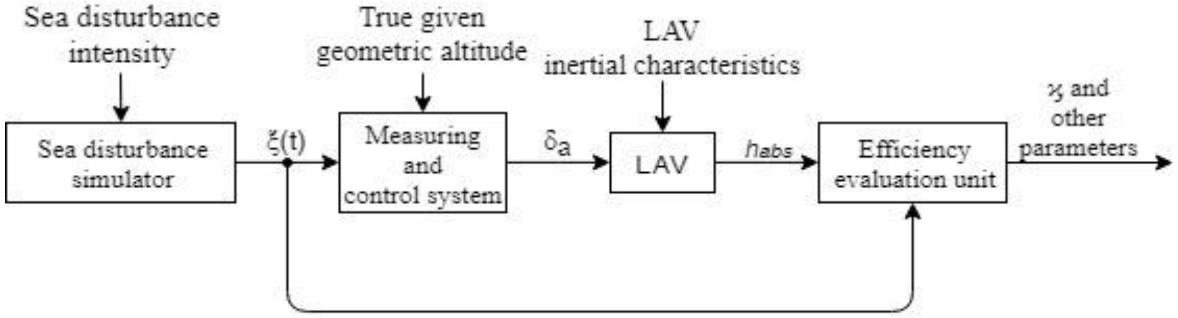

Fig. 2. Generalized block diagram of the simulation system for the motion of the low-altitude vehicle seeking to round the low-frequency components of the sea disturbance using vertical manoeuvring

The sea disturbance simulation unit is a white noise $w(t)$ generator that transmits a signal to the shaping filter. The output of the shaping filter gives the predicted ordinate value of sea disturbance $\xi(t)$. The specified parameter of this unit is the three percent supportability value $h_{3\%}$ of sea disturbance. This value is used to calculate the transfer function parameters of the shaping filter $H_V(s)$. The estimated value of the sea disturbance ordinate $\xi(t)$ is transmitted to the simulation unit input of the measuring and control system, in which the elevator angle $\delta_a(t)$ is calculated and then transmitted to the LAV motion simulation unit input. Motion simulation unit LAV generates the time dependence of the absolute altitude $h_{abs}(t)$ of the LAV seeking to round sea disturbance and determines to what extent the average value of the vehicle absolute altitude has decreased. A more detailed block diagram of the low-altitude vehicle motion simulation system is shown in Fig. 3. Parameters evaluation units for the shaping filter and the LAV dynamic simulation unit designate here as parameter calculation units PCU1 and PCU2, respectively, and *M* is an array consisting of elements $M_{Z0}^{\omega_Z}$, M_{Z0}^{α}, $M_{Z0}^{\delta_a}$, Y_0^{α}.

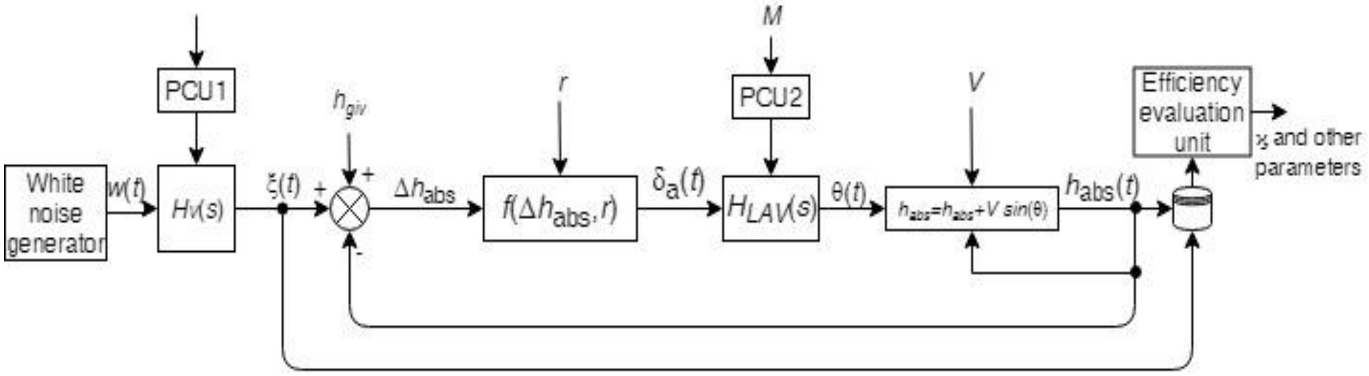

Fig.3. Block diagram of the low-altitude vehicle motion simulation system

The wave ordinate dispersion D_r, the correlation function parameter β and the attenuation coefficient α are calculated. For arisen wind disturbance, the ratio α=0,21 β is fulfilled. All these parameters are necessary to determine the spectrum of sea disturbance, from which the transfer function of the shaping filter is determined by factorization on complex-conjugate multipliers. The wave ordinate dispersion D_r is related to the sea disturbance altitude of three percent probability $h_{3\%}$ by the formula $D_r = 0{,}0358 h_{3\%}^2$.

Sea disturbance is described by exponential and rational spectra. Only rational spectra can be used for modelling of the sea surface using the shaping filter. They are slightly shifted relative to the exponential ones into the low-frequency region. The following spectrum was used in the work of (Lukomsky Ju. A. 1988).

$$S_h(\Omega) = \frac{4D_r \alpha \sigma^2}{\sigma^4 + 2(\alpha^2 - \beta^2)\sigma^2 + (\alpha^2 + \beta^2)^2}, \qquad (1)$$

with Ω as the sea disturbance spatial frequency. The maximum spectrum frequency Ω_m is determined by the ratio $\Omega_m = 1{,}42 \big/ \sqrt{h_{3\%}}$ and almost coincides with β, since $\Omega_m = \sqrt{\alpha^2 + \beta^2} = \beta\sqrt{1 + (\alpha/\beta)^2} = 1{,}02\beta$.

The shaping filter for a signal with such spectrum has a transfer function

$$H(s) = \frac{2\sqrt{\alpha D_r}\, s}{s^2 + 2\alpha s + (\alpha^2 + \beta^2)} \qquad (2)$$

Next, the difference between the desired absolute altitude by means of distance r and its current absolute altitude is calculated. Since the desired absolute altitude is the sum of the estimated wave altitude and the given value of the true geometric altitude, the formula takes the following form: $\Delta h_{abs}(t) = \xi(t) + h_{giv} - h_{abs}(t)$. After that, the formula $\theta = atan2(\Delta h_{abs}, r)$ determines the desired path inclination. The ratio of $\Delta h_{abs}(t)$ to r is the tangent of the desired path inclination. Elevator angle δ_a is calculated on the basis of (3) subject to calculated θ. The stabilization principle of the true geometric altitude of the vehicle due to vertical manoeuvring is explained in Fig. 3.

The function $atan2(x,y)$ is similar to the arctangent of x/y except that it has no discontinuities and is suitable for calculating the angle between the opposite leg of x and the adjacent leg of y. The function name is borrowed from the corresponding function in the programming languages C++ and MATLAB.

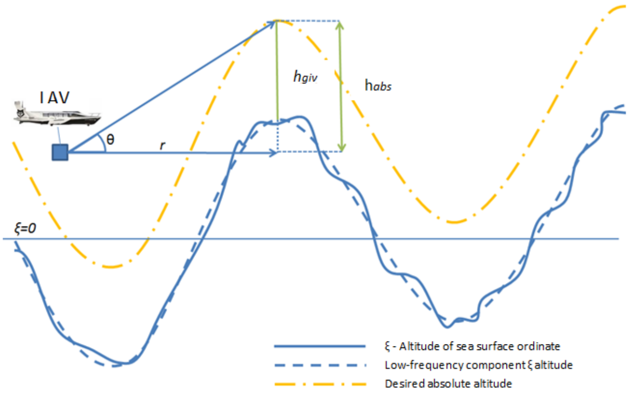

Fig. 4. Stabilization principle of the true geometric altitude of the vehicle due to vertical manoeuvring

Further, the path inclination is determined by the transfer function (3) of path inclination changing relative to the control action. After that, the absolute altitude at the next moment of time is calculated by the known velocity modulus and the path inclination.

The imaged equations of the aircraft longitudinal motion have the form

$$s^2\theta(s) + a_1 s\theta(s) + a_2\alpha(s) = -a_3\delta_a(s) + a_4 M_{BZ}(s)$$
$$-s\alpha(s) + a_5\alpha(s) + s\theta(s) = a_6 F_{BY}(s)$$

Let's exclude the variable α(s) from the equation and get the path inclination transfer function of the angle of the elevator angle

$$H_\theta^{\delta_a}(s) = \frac{a_3 a_5}{s\left[s^2 + (a_1 - a_5)s + (a_2 - a_1 a_5)\right]} \qquad (3)$$

with $a_1 = M_{Z0}^{\omega_Z} \big/ I_Z$, $a_2 = M_{Z0}^{\alpha} \big/ I_Z$, $a_3 = M_{Z0}^{\delta_a} \big/ I_Z$, $a_5 = Y_0^{\alpha} \big/ mV_0$, a_4 as specified coefficient, α(s) as angle of attack, $M_{BZ}(s)$ - disturbance torque, $F_{BY}(s)$ - disturbance force.

I_z - vehicle inertia relative to the axis OZ, $M_{Z0}^{\omega_Z}$ – variation of pitching moment due to pitching, M_{Z0}^{α} - static longitudinal stability, $M_{Z0}^{\delta_B}$ - control torque appearing in case of the elevator deflection of the horizontal tail, Y_0^{α} - vehicle lift force in case of the unperturbed motion, m - vehicle weight, V_0 - vehicle speed.

Reference to the formula (3) shows that it is necessary to know the vehicle inertial characteristics for the $H_\theta^{\delta_B}(s)$ task.

During the entire simulation time, the obtained values of the sea disturbance ordinate and the absolute altitude of the low-altitude vehicle are stored in the memory. Upon completion of the simulation, the reduction value of the absolute altitude average value is calculated by using the proposed method. Also, the efficiency evaluation unit can use other criteria for evaluating the method effectiveness, for example, increasing the aerodynamic quality of the vehicle using the ground effect.

3. SIMULATION RESULTS

Two-dimensional images of sea disturbance were obtained by simulation in Simulink.

For the 4-point sea disturbance $h_{3\%}$=2 m, whence it follows that D_r=0.143 m^2, $\beta = 1.004$ s^{-1}, α=0.210 s^{-1}.

$$H(s) = \frac{b_0 s}{s^2 + a_1 s + a_2} \tag{4}$$

For the 6-point sea disturbance $h_{3\%}$=6 m, whence it follows that D_r=1.289 m^2, $\beta = 0.5683$ s^{-1}, α=0.1193 s^{-1},

with $b_0 = 0.7843$ s $^{-1}$; $a_1 = 0.2386$ s^{-1}; $a_2 = 0.3372$ s^{-2}.

The transfer function (3) coefficients took the following values: a_1= 1.154 s^{-1}; a_2 = 1.40 s^{-2}; a_3= 0.427 s^{-2}; a_5=0.415 s^{-1}. These values were determined based on the average inertial characteristics of small and medium-sized low-altitude vehicles, taken from open sources. Some characteristics are given in (Yun Liang et. al., 2010; Michael Halloran et. al., 2015; Abdul Ghafoor et. al., 2015; Nebylov A.V. et. al., 2002). A fragment of the optimized trajectory during the flight under 6-point sea disturbance is shown in Fig. 5.

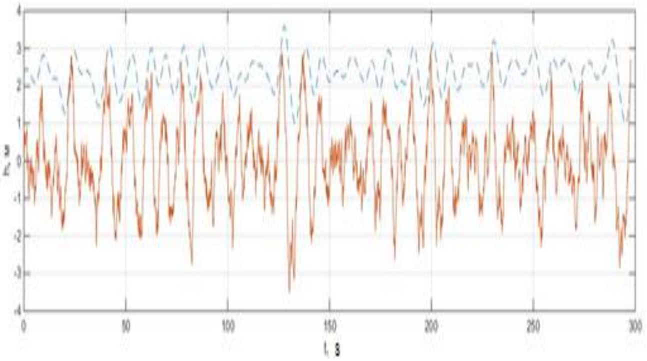

Fig. 5. Fragment of the vehicle motion path (dotted line) and 6-point sea disturbance (solid line)

In rectilinear motion, the true average geometric altitude is 3 m; when moving in the altitude minimization mode with zero reaction delay, the average true geometric altitude was equal to 2.35 m.

Since in solving the problem of the true geometric altitude stabilization, the LAV is forced to perform intensive manoeuvres almost continuously, it is important to assess the overload $n_y = V\theta'/g$. The acceleration response transfer function from the path inclination changing has the following easy form

$$H_{n_y}^{\delta_a}(s) = -\frac{Vs}{g} H_{\theta}^{\delta_a}(s) \tag{5}$$

A fragment of the time dependence of the vehicle overload is shown in Fig. 6.

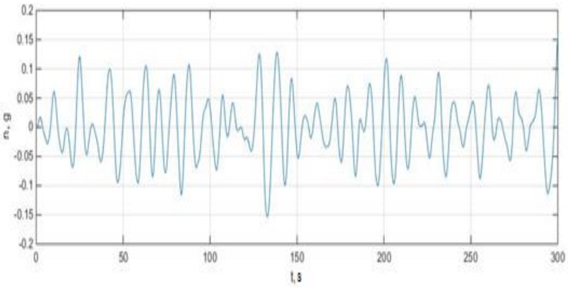

Fig. 6. Fragment of time dependence of the vehicle overload

In the first 300 seconds, the maximum overload modulus has achieved 0.15g at 130th second of flight. Throughout the flight, the overload did not exceed 0.16g. It is indicated that with weak turbulence, aircraft passengers experience an overload of 0.8-1.2 g, and with a storm overload exceeds the value of 2g. The most unpleasant and annoying is the effect on any person of low-frequency overloads with a frequency of 0.1-0.5 Hz given in (Aleksakhin B. N, et al., 1972). But due to the low magnitude, the overload resulting from vertical manoeuvring to minimize altitude the average geometrical altitude of flight is acceptable. In addition, it is possible to secure the crew and passengers from overloads using anti-overload protection, the method of operation of which is described in details in (Skrjabin E. F. et al., 2014; Staroverov N. E., 2017; Gorkova M.V., 2017); Staroverov N.E. 2008; Nebylov A.V., N. Tomita, et al, 2000; Nebylov A.V., Watson J., 2016).

4. CONCLUSIONS

The article proposes to minimize the true average geometric altitude of the low-altitude vehicle near the sea surface due to the tendency to round the low-frequency components of the sea disturbance using vertical manoeuvring. It allows to reduce radar visibility for the vehicles using the ground effect to increase their aerodynamic quality. The study of radar visibility reduction and aerodynamic quality improvement is the direction of further investigation.

The feasibility of striving around the low-periodic components of sea waves due to vertical maneuvers was determined by modeling. The spectrum of sea waves and the transfer function of a small low-flying vehicle were taken as the initial data for modeling.

The simulation results have shown the possibility of reducing the altitude of a highly manoeuvrable low-altitude vehicle at 6-point sea disturbance, when the altitude is $h_{3\%}$ =6 m, by 0.65 m. The effectiveness of the proposed method of minimizing the altitude shall be evaluated for a specific model of low-altitude vehicle.

5. FURTHER DIRECTION OF RESEARCH

This study is fundamental research and its purpose was not to obtain accurate estimates of the effectiveness of minimizing the altitude of certain aircraft models with known technical characteristics. In the future, the authors plan to study the influence of the proposed method of enveloping the low-frequency components of the intensive sea waves due to vertical manoeuvring on the movement of certain types of non displacement UAVs.

6. APPENDIX

Types of aircraft for which it is possible to use this control method:

WIG;

Hovercraft;

Hydrofoils;

Gliders;

Marine aircraft and helicopters moving at low speed at low altitude;

Military aircraft.

Table 1

Table of geometrical characteristics of sea waves

Grade, points	Average wave height, m	The average wave length, m	The average width of wave, m	Description
0	0	-	-	Calm-glassy
1	0-0.1	0-2	0-6	Calm-ripped
2	0.1-0.5	2-10	6-30	Smooth-wavelet
3	0.5-1.25	10-25	30-75	Slight
4	1.25-2.5	25-50	75-150	Moderate
5	2.5-4.0	50-80	150240	Rough
6	4-6	80-120	240-360	Very rough
7	6-9	120-180	360-540	High
8	9-14	180-280	540-840	Very high
9	>14	>280	>840	Phenomenal

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