FLIGHT AUTOMATIC CONTROL SYSTEMS FOR THE WING-IN-GROUND EFFECT CRAFT BUCHON-1

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Abstract: WIG-craft (Ekranoplanes) are taking up the transition between ships and aero planes and they are supposed to take the significant part of the projected air traffic growth without constructing new airstrips and aerodromes. Nowadays some countries have taken deep interest in this technology and started to work in the development of this promising and advanced kind of transport. The Venezuelan WIG Effect craft project called BUCHON-1 is one of them and it is projected to be used as a transport vehicle in the Caribbean Sea. However, a trouble-free flight at very low altitude over the disturbed sea surface and also for marine landing requires the application of special methods and means of motion control which are capable to solve the corresponding specific problems. Methods of providing stability to WIG Effect flight by special automatic control systems and the development of special altimeters are analyzed especially considering the BUCHON-1 and the experiments and tests extensively carried out using its prototype. The control means and algorithms developed especially for ekranoplanes are described.

Keywords: flight control, low altitude flight, marine landing, sea waves, radioaltimeter, sensors integration.

1. INTRODUCTION

Wing-in-Ground (WIG) Effect vehicles use the influence of the supporting surface applying the aerodynamics characteristics of special aerofoil, which result in the increase of lift and the decrease of induced drag. The sea surface is constantly gaining importance as the zone of flying vehicles operation. Hovercraft and other undisplacement vessels successfully used advantages of motion close to the supporting surface long ago. Aviation also aims to master better the denoted border layer of atmosphere in accomplishing the precise manoeuvres with reference to vessels, in arranging the search & rescue operations over the sea, in surrounding the underwater space, in using sea as a platform for take-off and landing. For the WIG-craft the flight near the surface is the natural mode of motion, but many control problems arise at providing the safety and effectiveness of such flight.

WIG vehicle or Ekranoplane as it is called in Russia is a winged amphibious vehicle with the ability of flight at extra low altitude where the lift/drag ratio grows considerably due to the effect of supporting surface. In this case the dynamic air cushion appears in the space between the wing and “screen” (which may be the surface of water, ice, or land) and its influence is added to the normal mechanism of lift force formation due to different speeds of air flow about upper and lower wing surfaces. It is a phenomenon of aerodynamic, aeroelstic and aeroacoustic effects when flying close to the supporting surface. WIG crafts also provide the opportunity to integrate many facilities and characteristics of a ship and an aircraft in one vehicle which is a very rare property hardly available for vehicles which may be used for both for civilian purposes as well as for military applications and missions.

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The velocity of WIG-flight for the Buchon-1 would be around 200-250 km/h. The vehicle length would be 13 m and the altitude has to be in the range from 0.5m to 3m.

The principal cities of Venezuela and industry centers are located close to the coasts in the Caribbean sea, the Maracaibo Lake and the Orinoco river (Fig.1), and 75% of the population is concentrated near to these coasts. The needs of passenger and cargo transportation rise constantly and in this area the WIG-craft technology is an excellent alternative for transport, while it becomes difficult and extremely expensive to build new aerodromes near these cities or use aeroplanes where airport infrastructure is not much developed and in some cases not available. There has also been keen interest expressed in Venezuela for the development of this technology especially for its Defense and Military applications, however, the exact details and status of such projects remain confidential. The BUCHON-1 is mainly for civilian transport and commercial applications.

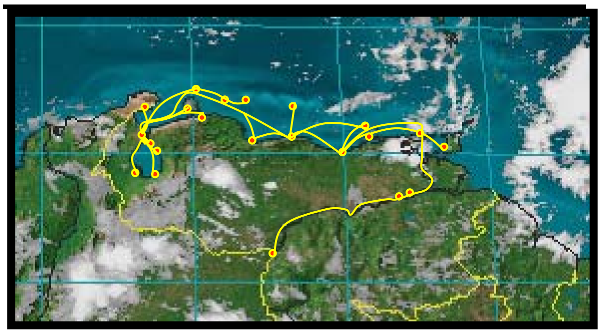

Fig. 1. Proposed Routes for the BUCHON-1 in the Caribbean Sea of Venezuela

Just for comparison in the Maracaibo-Caracus route it may be stated that WIG Effect crafts will take 4.00 hrs. and $25, buses take 12.00 hrs. and $20, ships take 14.00 hrs. and $70 and aircrafts take 45 min. and $140. Thus WIGs turn out to be one of the best transport vehicles in the region.

Aside from the high speed, the important advantages of a WIG-craft are:

- Absence of necessity for a runway and possibility to perform special transport operations using amphibian property, they can take-off or land from the surface of land, water or ice;
- Higher safety of flight due to the possibility of urgent ditching;
- Low contamination of the ambient;
- Reduced requirements towards engines reliability and, therefore, possibility of their fuller use of service life;
- Tight cabin and special life-support systems for crew and passengers are not necessary;
- Cost of construction, maintenance and exploitation below aviation (may be two times lesser);
- High transport profitability on midranges (about 1000 km) in matching with aircraft because of absence of energy consumption for rise on a high altitude;
- Use as Patrol Vehicles for anti-drugs and anti-smuggling operations where ships, hydrofoil vehicles and helicopters are very slow.

Probable areas for the most effective application of WIG-craft are:

- Passenger and cargo transportation between seaside cities and inland areas;
- Transportation of a perishable cargo from the regions with undeveloped transport network;
- Search & Rescue activities in the marine environment;
- Ecological monitoring;
- Tourism Operations, of visual review of dynamically varying picture of a marine and coastal landscape from an altitude of a deck of a cruise liner.
- Quick Transport of perishable goods (for example fishery exploitation).
- Servicing and Maintenance of Oil Rigs;

2. PECULIARITIES OF MOTION CONTROL

For motion of WIG-craft near the surface it is necessary to take into account a series of specific physical characteristics, related with the influence of the WIG-effect on aerodynamic forces and moments (fig,2). WIG-effect is an interesting physical phenomenon with multilateral characteristics, having positive and negative influence for providing the flight at extremely low altitudes (fig 3).

Fig 2. Russian Ekranoplane Orlyonok

The orientation of the wing relative to the ground is changed simultaneously with a change of attack angle $\Delta\alpha$ (fig. 3). The altitude of all points of the wing from the ground are changed, except the point corresponding to the axis of turn. Therefore, for example, an increment of wing lift force is determined with an increment of attack angle and an essential feature of the manifestation of ground effect is the fact of pitching aerodynamic characteristics of aircraft which depend not only on attack angle and on the altitude of wing above ground (h), but are also determined ambiguously with attack angle, since they depend on factors which have led to the forming of attack angle (α): a change of pitching angle (Θ) or presence of vertical velocity (h).

Notice, that the modern ekranoplanes have in the majority a plane-like aerodynamic configuration with a wing of small outstretched index and highly raised tail stabilizer (with a large are). However, the promising large ekranoplanes are designed under the scheme "combined wing" having a number of advantages.

For the essential action of WIG-effect the altitude of ekranoplane flight has to be less than a half of the wing chord. The size of ekranoplanes should allow to maintain an optimal altitude at cruise mode and not be too limited by the height of sea waves. The Buchon-1 (fig. 4) is designed with a wide fuselage and airfoil shape to take the most possible advantages from ground effect and with a Canard wing for the control of the pitching angle which is connected to the automatic control system. Anyway it is necessary to choose the extremely low flight altitude, permissible as to criterion of flying safely at the definite height of sea waves. Even if the vehicle has the natural properties of self-positioning and self-stabilization as to the altitude and the inclination angles, only the facilities of automatic control can ensure the required functional characteristics under the circumstances of rough sea and high sea waves.

Unfortunately, an ekranoplane has the essential instability of motion in the longitudinal plane and perfect automatic control system is necessary first of all for providing the flight stability. For heavy machines the automatic control systems are required definitely. For smaller ekranoplanes many attempts to exclude any automation of motion control are known, but only the grim necessity to lower the cost of commercial vehicles causes such attempts that certainly degrade the safety of motion.

Trouble-free motion close to the disturbed sea surface may be guaranteed by the application of special methods and means of navigation and control, which must have the capability to solve the following specific problems (Nebylov, 1996, 2002):

- The precise control of the altitude of motion with the error not above 3-10 cm;
- Restricting the angles of airframe inclination for prevention of undesirable tangency of water by the extreme points of body or wing;
- Ensuring of the vehicle stability in the circumstances of the action of flake non-linear aerodynamic effects near the surface;
- Non-contact measurement, tracking and prediction of ordinates and biases of the field of sea waves for the rising of motion control effectiveness.

Certainly, the automated control for WIG-craft is a necessity to prevent accidents and the automation of motion control has to be callable for all ekranoplanes.

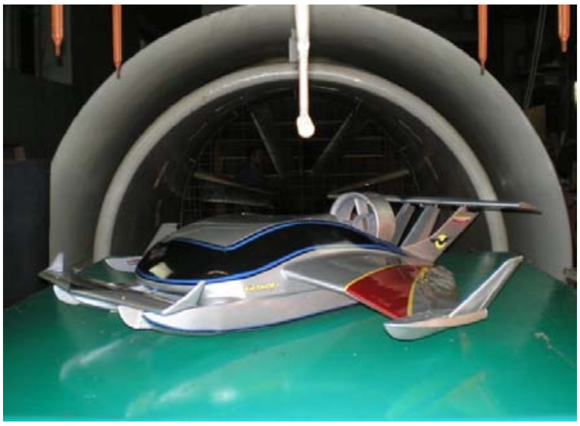

Fig.3. Buchon M-1 Model during wind tunnel tests in Russia.

3. STABILITY PROBLEM

Ever since the very first experimental WIG-craft were been built, longitudinal stability has been recognized as a very critical design factor. When not designed properly WIGs show a potentially dangerous pitch up tendency when leaving (strong) ground effect (Fig. 6). Powerboats sometimes show the same tendency, when they meet a wave or a wind gust and may suddenly flip backwards.

The reason for this behavior is the fact that the working line of the lift vector of a wing is located relatively far aft at very small ground clearances and moves forward when climbing out of ground effect. The stability problem can be overcome by installing a relatively large horizontal tail and although a WIG craft cannot be stabilized by c.g. movement alone, the location of the c.g. is very important for achieving acceptable longitudinal stability.

Some wing plan forms are more stable than others, the reversed delta from Lippisch proved to be very good, therefore it has been very popular lately (e.g. in the Airfisch series craft). Not only the plan form, but also the wing section is important for stability. Recent research showed that wing sections with an S-shaped camber line are more stable than conventional wing sections (Fig. 7). The BUCHON-1 implements very carefully all these parameters.

WIG-craft as the controlled plant has an essential specificity in comparison with an ordinary plane, connected with a sharp non-linear dependence of all aerodynamic coefficients and character of their correlation on a relative altitude of flight $h_r = h/b$, where h is an altitude of centre of gravity of ekranoplane concerning an average level of wave surface, and b is the chord of wing. Great specificity exists also in the wave disturbances.

When flying far from the supporting surface, an ekranoplane, like an airplane, can have longitudinal stability if its center of gravity is ahead of aerodynamic center. At correct center of gravity positioning, aerodynamic center in airplane flight depends slightly on angle of attack providing fulfillment of this condition with a certain margin.

In the supporting surface action zone the longitudinal stability can be disturbed because the aerodynamic force depends not only on the attack angle but also on motion altitude. Besides, aerodynamic center position may vary depending upon several factors under supporting surface influence. When the altitude decreases, focus moves backwards due to pressure increase at the wing back edge area under positive angles of attack and moves forward - under zero and negative angles of attack.

As the lift force of a wing increases with relative height h_r decreasing, the achievement of the natural stabilization of a flight altitude is possible. However, the range of inherent stability in the space of flight parameters is usually very narrow. In this connection the automatic control system must not only prevent escaping this range, but also essentially correct the dynamic properties of ekranoplane for increasing a stability margin for all controlled parameters of motion. The activity of the channels of damping and stabilization of altitude and pitch is especially relevant.

Undoubtedly, the effective means of stable motion area extension and even of formation of such an area for structurally unstable craft is by use of special autopilots for WIG-craft.

4. CONTROL LAW SYNTHESIS OF BUCHON-1

It is possible to execute the altitude control under the change of wing lift force in:-
a) Trailing-edge flap deflection;
b) Elevator deflection (thus a pitch varies);
c) Change of speed of flight at the expense of engines thrust control;

As at pitch angle variation, the drag and, therefore, the flight speed changes, the version *b)* demands the presence of velocity stabilization system. Thus all channels of the control complex substantially participate in the maintenance of the ekranoplane demanded motion in the longitudinal plane. The synthesis of control laws can be fulfilled under the several criteria, but their general structure appears to be almost similar in the majority of cases. The estimations of the vehicle stabilization errors, linear and angular rates and also wave disturbances, being filtered accurately, have to be used at the formation of control signals. Now the main problem of a good accuracy and measurement instruments for WIG crafts has been solved with the development in IIAAT of the Phase Radio Altimeters (RA) specially designed for low fly altitudes under the guidance of Prof.A.Nebylov.

The flight parameters measuring system was designed for an experimental WIG-craft It is intended for control and record of flight parameters:
- Altitude of flight up to 5 m with accuracy 5 cm;
- Speed up to 180 m/s with accuracy 0.1-0.2 m/s;
- Roll and pitch angles with accuracy 0.1-0.2 deg;
- Vertical overloads up to 3g with accuracy 0.06g;
- Considerable sea waves height up to 1.5 m with accuracy 5 cm.

Primary sensors were: 3 special radioaltimeters, vertical reference system, multi-antennas DGPS receiver, etc. They were integrated with the aim of improving the accuracy and providing the fault-tolerance properties.

The characteristics of RA (Fig. 4) are:-
- Altitude (or distance) measured - 0-10m;
- Measurement error - not more than 5 cm under sea state number 0-5;
- Measured parameter frequency range - 0-50 Hz;
- The operating RF - from X-range (9000 MHz);
- Radiated power - 20 mW;
- Power consumption - 2 W;
- Output signal - digital and analog;
- Mass - 1.2 kg;

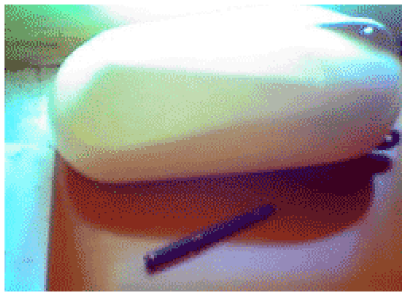

Fig. 4. Precise Phase Radio Altimeter (RA)

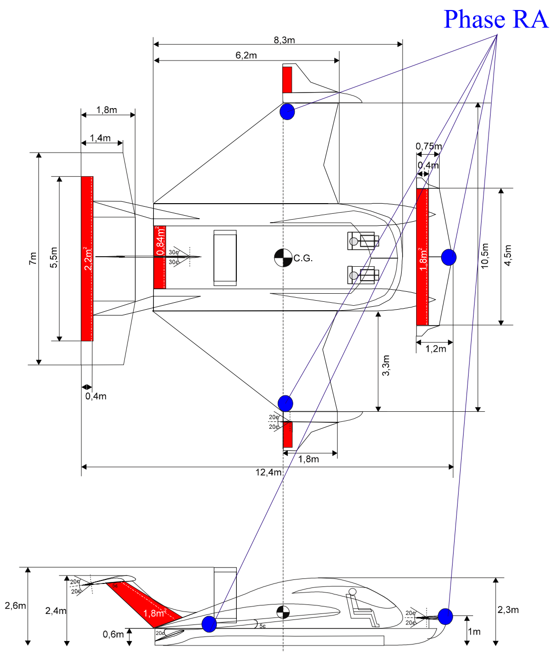

Fig. 5. Application of RA for WIG-craft Buchon-1

5. SPECIAL CHARACTERISTICS OF BUCHON-1

1. Its Fuselage helps to produce more lift and horizontal stability(due to the blended-wing structure), closing the air under it to take advantage of the ground effect during the takeoff and cruise while greatly reducing the minimum take-off distance.

2. The canard also helps during the takeoff and landing producing a high angle of attack at low velocity. It can be used together with the elevator for the longitudinal stability of the ship during cruise to prevent the canard and the main wing from looping.
3. The canard wing generates positive lift at the moment of takeoff/alighting. On the contrary, horizontal tails in the conventional concept generate negative lift at the moment.
4. The elevator and rudders are effective even in a slow forward speed because they are in the propeller wake and always supplied with accelerated air stream. It enhances the safety in low-speed navigation.
5. The catamaran hulls are constructed with a system to reduce the drag on the water. The system consists in take 10% of the exhaust air of the propulsion to produce a hovercraft effect under the hulls (fig. 6).
6. Propulsion system is in a spray free region, so it leads to the low maintenance cost and good durability of the system.

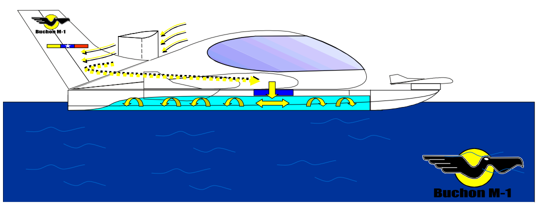

Fig. 6. Lift Aid System for reduced hydrodynamic drag in the Buchon-1

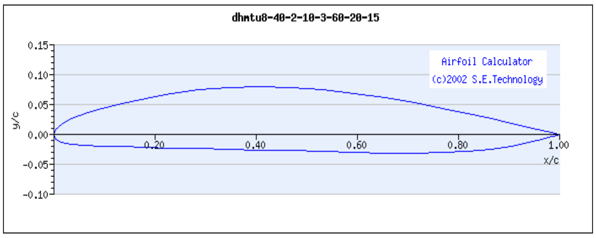

Fig. 7. Special wing section for ground effect used in the BUCHON-1

6. DEVELOPMENT OF CONTROL SYSTEMS FOR BUCHON-1

Structure of algorithm of a complex filtration of measurements of RA and vertical accelerometer on the channel of height will be installed for the measurement of height, pitching angle and banking.

The algorithm of complex filtration of measurements of RA and vertical accelerometer includes in (Fig 8).

- The block of recalculation of measurements RA on a point of installation Inertial Unit (IU);
- The block of recalculation of an estimation of altitude from a point of installation IU on CG ;
- The filter of altitude (Filter 1);
- The filter of vertical acceleration (Filter 2).

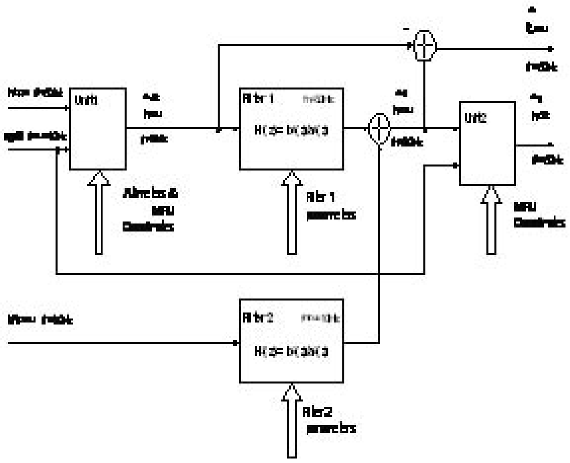

Fig.8 The block diagram of algorithm

With the use of three described radioaltimeters, the integrated system for measurement of parameters of motion close to a sea surface can be built, the compact INS is also included in the system. This INS (of MRU type) involves three angular-rate sensors, three linear accelerometers, calculator and temperature transmitter for compensation of temperature drift of angular-rate sensors and accelerometers.

The structure of integration algorithm for altimeters and vertical accelerometer output signals is shown in Fig.9 and involves:

- The unit of recalculation of altimeters outputs to a point of IU installation (Unit 1);
- The unit of recalculation of the altitude estimations to the point of centre of gravity CG and to the points of altimeters installation (Unit 2);
- The filter of an altitude (Filter 1);
- The filter of a vertical acceleration (Filter 2).

The recalculation of altimeters outputs to CG is executed under the formula

$$h_{GC\_K} = h_k - x_k \psi + z_k \theta - y_k ,$$

where the index k=n,l,r (n - nose altimeter, l - left side altimeter, and r- right side altimeter. For recalculation of altitudes from a point of CG to a point of INS installation the relation

$$\hat{h}^{Ail}_{INS} = \underset{k}{med}\,(h_{GC\_k} + x_{INS}\,\psi - z_{INS}\,\theta + y_{INS})$$

is used, where med (.) is the operation of median definition. The formula for recalculation of the filtered value of an altitude from a point of the IU installation to CG (Unit 2) looks like:

$$\hat{h}^{f}_{GC} = \hat{h}^{f}_{INS} - x_{INS}\,\psi + z_{INS}\,\theta - y_{INS} .$$

The filters of an altitude and vertical acceleration have the transfer functions

$$H_1(s) = \frac{\tau^2 s^2 + 2\tau k_3 s + k_3}{s^3 + \tau^2 k_3 s^2 + 2\tau k_3 s + k_3},$$

$$H_2(s) = \frac{s}{s^3 + \tau^2 k_3 s^2 + 2\tau k_3 s + k_3},$$

where $k_3 = 0.035\ \mathrm{s}^{-3}$, $\tau = \frac{1.32}{\sqrt[3]{k_3}} = 4.035s$.

In discrete time the structure of filters is described by the formulas

$$H_1(z) = \frac{b_2^1 z^2 + b_1^1 z + b_0^1}{z^3 + a_2^1 z^2 + a_1^1 z + a_0^1},$$

$$H_2(z) = \frac{b_2^2 z^2 + b_1^2 z + b_0^2}{z^3 + a_2^2 z^2 + a_1^2 z + a_0^2}.$$

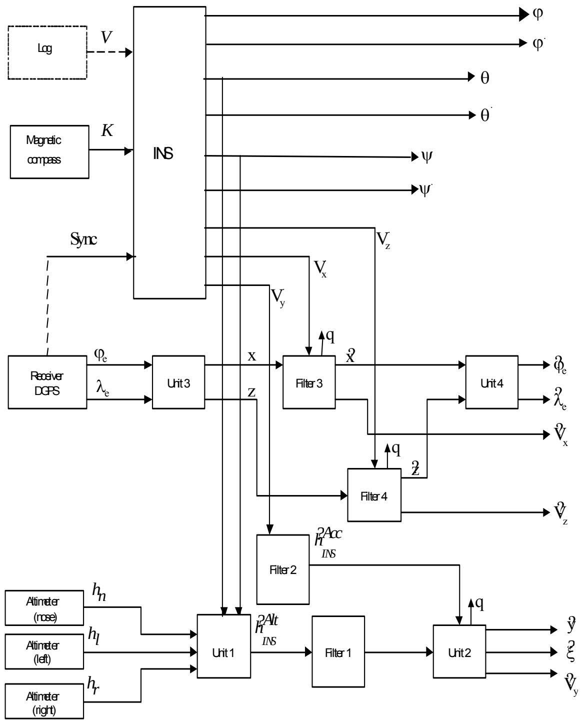

Fig. 9 Block-diagram of the integrated measuring system.

The measuring system allows to track the profiles of sea waves ξ_n, ξ_l, ξ_r in three points, corresponding to the points of radioaltimeters installation at a nose and both sides of the vehicle, with the accuracy 10 cm at seaway number 4. Separately, that is important for optimization of a mode of landing approach and splashdown. Separately the problem of automatic estimation the general direction of sea waves spread was solved, that important for the optimization of landing on water.

The problem of automatic estimation of the general direction of sea waves propagation with the use of three radioaltimeters outputs will be lighted.

The following criteria of automatic control quality for BUCHON-1may be considered:-

- Stability provision of motion in the longitudinal plane;
- Rise of seagoing ability of a vehicle, i.e. its capability to move in given direction and to solve another functional tasks at the largest number of sea conditions;
- Reduction of fuel consumption;
- Depression of vehicle rocking for creating the favorable conditions for crew and passengers or for functioning of on-board equipment.

Naturally, it is impossible to reach the extremum of all these criteria simultaneously and each concrete case requires appointing the only main criterion of control effectiveness, and transforming other ones to the rank of limitations. Amongst the number of limitations is also necessary to denote the necessity of economical expenditure of control elements resources.

7. CONCLUSION

The demanded characteristics of vehicles for flight close to surface can be achieved only by the use of the new capabilities of perfecting the systems of navigation and motion control created by modern means of supply with flight information and by resources of on-board computers. All physical specialties for motion close to the surface have to be carefully analyzed and taken into account. The control algorithms and some hardware of automatic control systems of ekranoplanes differ essentially from airborne ones and require the special research and design. Some new results in this field have been developed for BUCHON-1 and have been described in this paper.

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