Back to Session Subjects

FEATURES INHERENT IN DESIGNING MI-60 MAI SUPERLIGHT HELICOPTER POWERED BY TWO PISTON ENGINES

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Abstract

The main problems to design a superlight helicopter developed jointly by MAI, MMHP and Rostvertol joint-stock company are discussed. One of the main requirements for the helicopter design is a twin-engine power plant that will allow the helicopter to increase safety of its operation and to fly over cities. The comparative analysis of the piston engine characteristics is given for the given class of helicopters. Reasons used in the selection of the main parameters of the helicopter main rotor are given. The helicopter performance with one engine inoperative and the results of mathematical modelling of one engine failure in hover are presented. Possible control laws ensuring helicopter rotor attaining the design speed with one operating engine are analysed. On the basis of the helicopter descent dynamics with one engine inoperative the boundaries of the left and right dangerous V-H areas are determined. It is shown that the twin-engine helicopter provides the necessary level of safety with one engine inoperative.

1. Introduction

Since 1995 a superlight multipurpose helicopter has been designed at the MAI Helicopter Design Department to the specification of the Ministry of Science of the Russian Federation. Mil Moscow Helicopter Plant JSC and Kamov JSC participate in this activity too. It is intended for initial pilot training, air patrol, environmental monitoring, communication, etc.

At first, the helicopter was to carry one passenger or an equivalent load in the environmental conditions and infrastructure inherent in Russia [1]. In 1998 MAI, Mil Moscow Helicopter Plant JSC and ROSTVERTOL JSC signed an agreement about carrying out this project: with Rostvertol JSC and Mil Moscow Helicopter Plant JSC acting as the Customer and the General Designer respectively. The helicopter got its designation: *Mi-60 MAI* [2].

At the Customer's request the helicopter concept was changed. The helicopter size was changed so that the helicopter could carry one pilot and either 1-2 passengers or an equivalent payload. One of the main requirements was as follows: the helicopter should be powered by a twin engine power plant to improve its flight safety and ensure its flights over cities.

The main advantage achieved by any twin-engine helicopter is its highly improved flight safety compared to that provided by a single-engine helicopter. This allows the helicopter to be certificated for commercial operations in Category A. At the same time, the twin-engine power plant will allow light helicopters to widen their application, particularly for commercial operations. Some missions at present performed by larger helicopters could be carried out by the Mi-60 MAI at much lower costs and much more effectively.

There is quite a great range of light helicopters in the world market (such as *Shweizer 300 CB, Robinson R-22, R-44, Enstrom E-28, E-280 FX)* whose price is within 110,000-200,000 US dollars. Expensive piston engines operating on high-octane aviation gasoline power them. All the above helicopters are single-engine ones, therefore they cannot be used by airlines. Only helicopters whose TOW is more than 1,500 kgf are used for commercial operations in foreign countries, and the category of lighter twin-engine helicopters is fully missing.

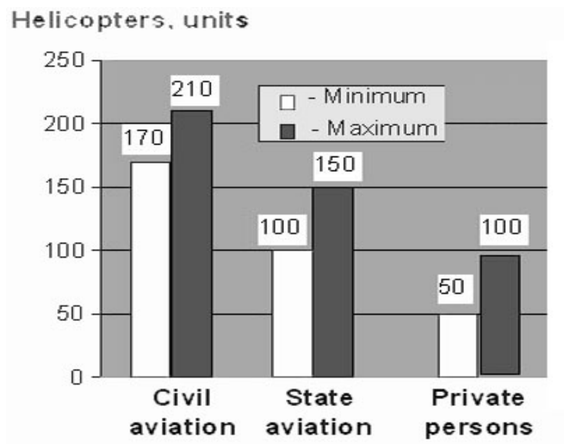


Fig. 1. Potential Demand for Mi-60 MAI Helicopters in Russian Market.

When the *Mi-60 MAI* was conceived, an analysis of its potential operators and its estimated price was made. The following conclusions were made proceeding from the results obtained. The estimated demand for the *Mi-60 MAI* in the Russian market was 400-600 units. The main customers (Fig. 1) could be: civil aviation (to carry passengers, to perform aerial chemical jobs, air patrol, environmental monitoring), state authorities (such as Frontier Guards, Militia, Customs, Road Traffic Safety State Inspectorate, Ministry for Emergency Situation, etc.), private persons. In case 500 units and more are produced, the estimated price of *Mi-60 MAI* helicopter would be approximately 140,000-170,000 US dollars. Fig. 2 shows price comparison for light helicopters available in the world market.

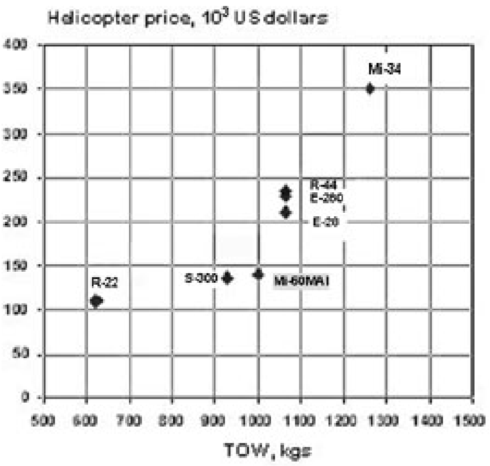


Fig. 2. Light Helicopter Price Comparison

Contradictory technical and economic requirements for a light twin-engine helicopter make it a must to look for optimal design solutions at the preliminary design stage. The paper considers some of the problems arisen in the *Mi-60 MAI* design process and the ways of solving them are offered.

2. Engine Selection for Helicopter Power Plant

One of the main problems to be solved in designing light helicopters is an engine selection. The analysis of the aircraft engines available in the world market has shown that at present no gas turbine engines with takeoff power of up to 200 hp are available. On other hand, the prices of the engines available are twice as high as those of the piston engines of the same power.

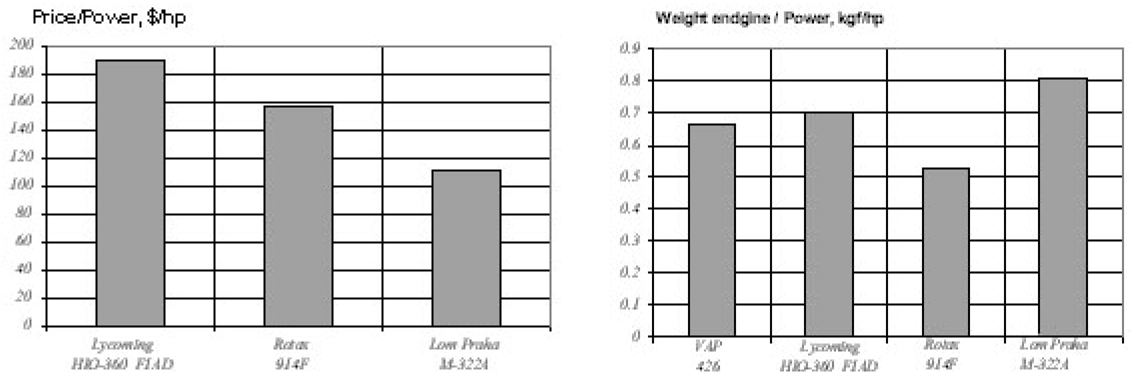
Having analysed he Customer's requirements for the *Mi-60 MAI* helicopter from the point of view of its purpose, cost and production volume, four piston engines made by different manufacturers were selected for further studies. Table 1 shows comparative performance of the following aircraft piston engines: *Lycoming HIO-360-F1AD, VAZ-426, Rotax 914F* and *M-332A.*

As far as the specific cost is concerned, the diagrams obtained from this data (Fig. 3a) show that the *M-332A* engine (Fig. 4) has the best performance among the options. A helicopter powered by two of these engines will be the cheapest, all other things being equal. In addition, the *M-332A* has the Russian Type Certificate and can operate on high-octane automobile fuels and lubricants which greatly widens the geography of those regions where the helicopter can operate. The above factors combined with a long service life of the engine make it most preferable for use in the *Mi-60 MAI* helicopter.

T a b l e 1

Basic Parameters and Performance of Aircraft Piston Engines

	Unit of measure	*Lycoming HIO-360 F1AD*	*VAZ 426*	*Rotax 914 F*	*M 332A*
Power ratings :					
takeoff	hp	190.0	240.0	115.0	140.0
normal	hp	190.0	213.0	100.0	115.0
cruising	hp	142.0	160.0	90.0	97.0
Weight	rgf	13.3,0	160.0	61.0	113.0
Engine speed (normal)	rpm	3,050	6,000	5,500	2,550
output shaft speed	rpm	3,050	2,800	2,260	2,550
Cylinders: number		4	3 sections	4	4
arrangement		opposite	single row	opposite	single row
Direction of rotation		LH rotation	LH rotation	LH rotation	LH rotation
Specific fuel consumption	kgf•hp/h	0.228	0.195	0.198	0.206
Fuel grade		B91	B91 AI92	AI95	B91,92 A76,92
Cooling		liquid	liquid	mixed	air
Fuel system		injection	injection	carburettor	injection
Starter power	kW	1.0	-	-	1.1
Generator: voltage	V	24	-	-	28
power	W	960	-	-	900
Service life	h	2,000	-	1,200	2,000
Type Certificate		available	unavailable	available	available
Price	US dollars	36,000	-	18,000	15,600



a) specific cost **b) specific weight**

Fig. 3. Piston Engine Specific Characteristics.

However, the *M-332A* has quite an important drawback: it is the heaviest engine from those under study in terms of absolute and relative characteristics (Fig. 3b). The helicopter preliminary design showed that the frame fuselage fitted with two *M-332A* engines would have the take-off weight of 1,000-1,100 kgf when meeting all the specification requirements.

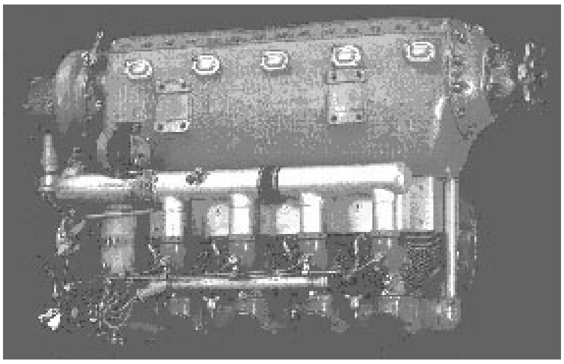


Fig. 4. Lom Praha M-332A Overall View.

3. Selection of Main Rotor Speed and Main Gear Box Reduction Ratio

Another problem in designing piston-engine helicopters is a selection of the rotor drive system parameters as well as the main and tail rotor speed.

A peculiar feature inherent in helicopter power plants using piston engines is the power available N_e-versus-engine crankshaft speed n_e relation (Fig. 5). This feature results in the fact that take-off and vertical flight conditions are carried out at a higher main rotor speed, while cruising is performed at a lower main rotor speed ensuring the engine maximum continuous power rating

Therefore, in designing piston engine helicopters a problem of selecting the main rotor speed n_M does arise. It should be selected so that it should ensure helicopter optimal performance and meet the engine operating limitations.

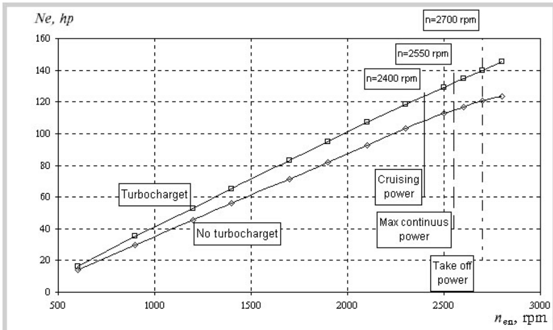


Fig. 5. External Characteristic of Lom Praha M-332A Engine

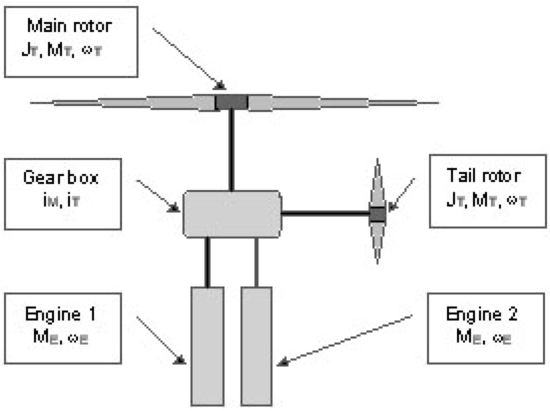


Fig. 6. Block Diagram of Helicopter Mathematical Model.

To select this parameter, i.e. n_M, two conditions were considered. The first one was to obtain the helicopter maximum TOW using the full power produced by the power plant in hover out of ground effect. The second condition was to obtain the helicopter maximum TOW in OEI flight at a speed for best rate of climb of 0.75 m/s. This FAR Part 29 requirement refers to Category A helicopters.

To analyse the first condition, parametric studies were made using a simplified mathematical model of the helicopter. Proceeding from the results of those studies the main gear box reduction ratio i_M and the main rotor blade tip speed $(\omega R)_M$ were selected. The block diagram of the helicopter mathematical model is shown in Fig. 6.

The torque M_e produced by the engines rotating at a speed ω_e, is transmitted through the main gear box with reduction ratios i_M and i_T

$$\omega_e = \omega_M\, i_M = \omega_T\, i_T \qquad (1)$$

to the main and tail rotors whose torques are M_M, M_T respectively. In this case the energy balance equation for the rotors-engines system is as follows:

$$M_M\omega_M + M_T\omega_T = k_e M_E \omega_e \zeta + \Delta N_{unT} = 75g[k_e N_e(n_e)\zeta + \Delta N_{unT}], \qquad (2)$$

where: ζ is the coefficient taking into account power losses caused by power transmission through the gear boxes and the flow around the body; k_e is the number of the engines operating; ΔN_{unT} is accessory drive power losses.

Differential equations describing unsteady main and tail rotor speeds, whose moments of inertia are equal to J_M and J_T, can be written as follows:

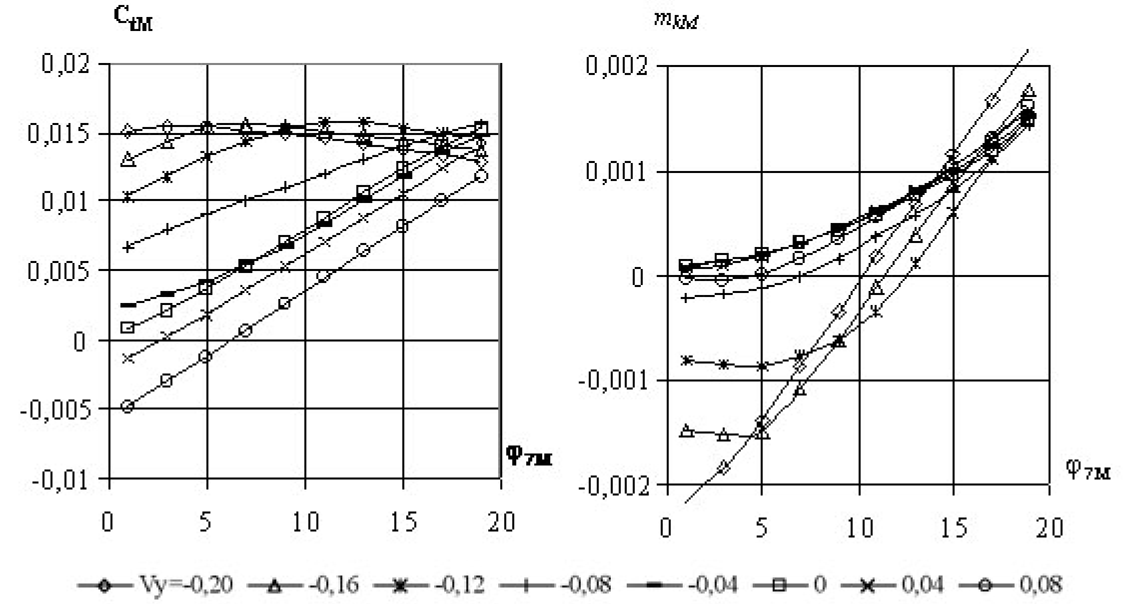


Fig. 7. Main Rotor Aerodynamic Characteristics.

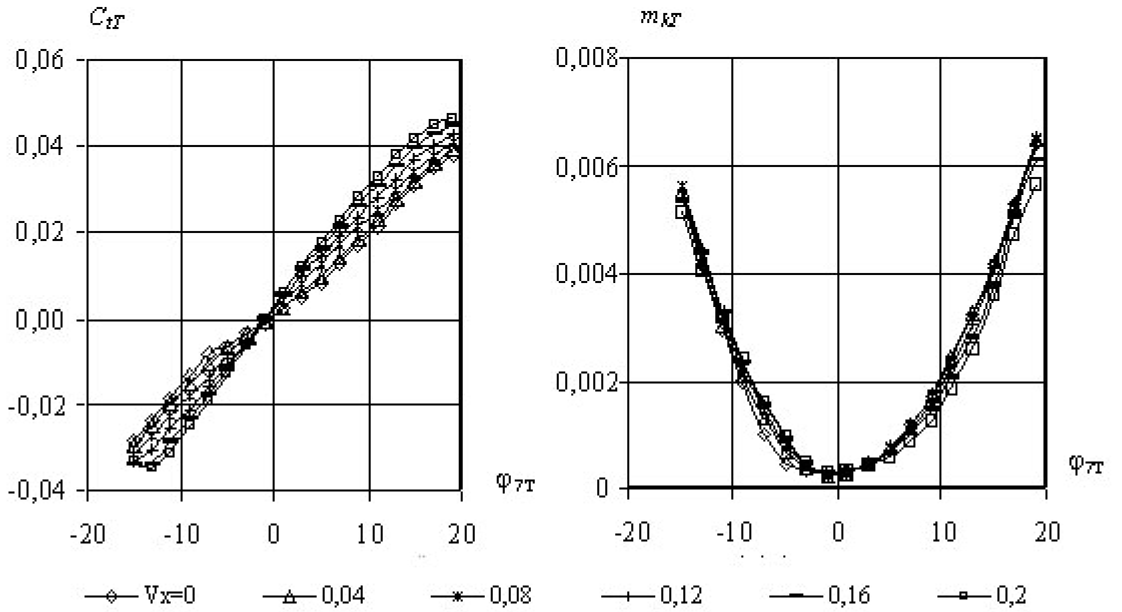


Fig. 8. Tail Rotor Aerodynamic Characteristics.

$$J_{\text{M}}\frac{d\omega_{\text{M}}}{dt} = M_{\text{M}} - M_{\text{кM}},$$
$$J_{\text{T}}\frac{d\omega_{\text{T}}}{dt} = M_{\text{T}} - M_{\text{kT}}, \tag{3}$$

where: M_{kM}, M_{kT} are rotational drag moments (torques) produced by the main and tail rotor shafts due to the aerodynamic forces applied.

Let us express M_{kM} and M_{kT} by using torque coefficients.

$$M_{\text{kM}} = m_{\text{kM}}(\varphi_{7\text{M}}, \overline{V}_{\text{yM}}, M_{0\text{M}})\frac{\pi\rho}{2}R_{\text{M}}^{5}\omega_{\text{M}}^{2},$$
$$M_{\text{kT}} = m_{\text{kT}}(\varphi_{7\text{T}}, \overline{V}_{\text{xT}}, M_{0\text{T}})\frac{\pi\rho}{2}R_{\text{T}}^{5}\omega_{\text{T}}^{2} \tag{4}$$

The thrust produced by the main and tail rotors will also be expressed by means of aerodynamic coefficients.

$$T_{\text{M}} = c_{\text{tM}}(\varphi_{7\text{M}}, \overline{V}_{\text{yM}})\frac{\pi\rho}{2}R_{\text{M}}^{2}\omega_{\text{M}}^{2},$$
$$T_{\text{T}} = c_{\text{tT}}(\varphi_{7\text{T}}, \overline{V}_{\text{xT}})\frac{\pi\rho}{2}R_{\text{T}}^{2}\omega_{\text{T}}^{2}. \tag{5}$$

The main and tail rotor operating conditions are connected to the helicopter directional trim.

$$M_{kM}=T_T L_T, \tag{6}$$

where L_T is the distance between the main and tail rotors.

Fig. 7 shows main rotor aerodynamic characteristics, i.e. $c_{tM}(\varphi_{7M}, \overline{V}_{yM})$, $m_{kM}(\varphi_{7M}, \overline{V}_{yM})$, used in the analysis, within the collective pitch variations of the blade typical section $1° \le \varphi_{7M} \le 19°$ and relative speeds of vertical flight $0.2 \le \overline{V}_{yM} \le 0.1$. Negative speeds mean descent, and positive ones, ascent.

Mach numbers for the main and tail rotors are determined by the blade tip speeds.

$$M_{0M} = a/(\omega R)_M,\ M_{0T} = a/(\omega R)_T. \tag{7}$$

Fig. 8 shows the tail rotor aerodynamic characteristics, i.e. $c_{tT}(\varphi_{7T}, \overline{V}_{xT})$, $m_{kT}(\varphi_{7T}, \overline{V}_{xT})$, within $15° \le \varphi_{7T} \le 19°$, $0 \le \overline{V}_{xT} \le 0.2$ used in the analysis. It should be noted here that any vertical displacement of the helicopter produces a condition of skewed airflow for the tail rotor with an angle of attack equal to zero. Therefore the inplane relative component of the stream velocity can be used as an argument for the torque coefficient m_{kT}.

$$\overline{V}_{yM} = V_y/(\omega R)_M,\ \overline{V}_{xT} = V_y/(\omega R)_T. \tag{8}$$

The following assumptions were used in the analysis made.

1. The ***MAI Mi-60*** main rotor diameter and blade chord were selected as being equal to 10 m and 0.22 m respectively proceeding from the *Mi-34* rotor system possible modification considerations.

2. The tail rotor parameters are not affected by any variation of the main rotor speed and provide the required directional control margin within all the operating conditions. Main and tail gearbox power losses depend upon the power transmitted and are assumed to be equal to 1.5% and 1% respectively. Power losses due to the fuselage airflow are 2%. So, the result is as follows: $\zeta = 0.965$.

3. To provide maximum power the engines are turbocharged with the throttle plate fully open (the upper curve in Fig. 5).

4. To provide air cooling each engine is fitted with a fan; to drive it, the power bleed in take-off is 10 hp (ΔN_{fan}=10 hp):

$$\Delta N_{unT} = 2\Delta N_{fan} = 2\times 10(n_e/2{,}700)^3,\ \text{hp}.$$

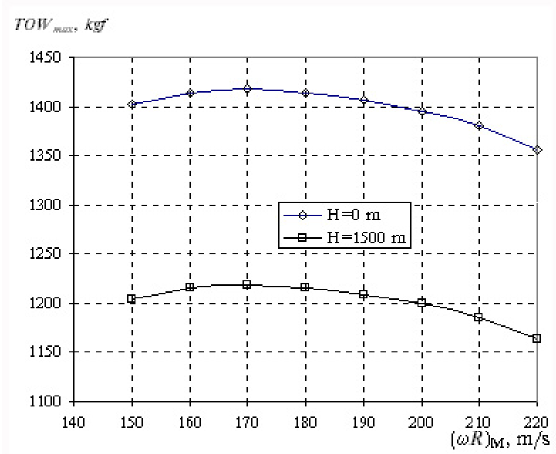


Fig. 9. Helicopter Maximum Take-off Weight versus Main Rotor Blade Tip Speed $(\omega R)_M$.

Fig. 9 presents the helicopter maximum take-off weight $G_{TOW\ max}$ -versus-blade tip speed $(\omega R)_M$ curve. The analysis was made for out-of-ground- effect hover, ISA, SL and 1,500 m altitude (i.e. hovering ceiling). The result was obtained by the numerical solution of equations (1)-(6) for steady operation of both engines turbocharged at the take-off power rating $n_E = n_{E\ take\text{-}off}$. The reduction ratio has its own value i_M for each $(\omega R)_M$ value.

The nature of the $G_{take\text{-}off\ max}(\omega R)_M$ relationship is generally determined by the main rotor profile power changes. An increase in $(\omega R)_M$ results in increased Mach number and wave losses. Any reduction in $(\omega R)_M$ results in increased angles of attack in blade sections thus deteriorating the L/D ratio and increasing the profile power.

The blade tip speed $(\omega R)_M$ of 70 m/s is optimal for out-of-ground-effect hover. In this case $G_{\text{take-off max}}$ = 1,430 kgf and 1,240 kgf is provided for hover at SL and 1,500 m altitude respectively, and the reduction ratio for the main gear box i_M will be 8.32.

However, there are two reasons due to which the blade tip speed is not recommended to be equal to $(\omega R)_{M\ opt}$. First, in this case $(\omega R)_M$ is 148 m/s at the engine cruising power rating which is unacceptable from the point of view of the stall condition. Fig. 10 shows that a reduction in the $(\omega R)_M$ relative to the $(\omega R)_{M\ opt}$ results in an increase in the main rotor coefficient t_y, and at the $(\omega R)_M$=150 m/s the working t_y exceeds its critical value caused by stall.

Second, to ensure helicopter flight within the preset altitude and temperature range without any main rotor blade stall limitations in ISA conditions, it is necessary to have $t_y \le 0.15 - 0.16$. The expected maximum take-off weight of the *Mi-60 MAI* helicopter will be 1,200 kgf. Therefore, at $t_y \sim 0.15$ the blade tip speed should be about 195 - 197 m/s.

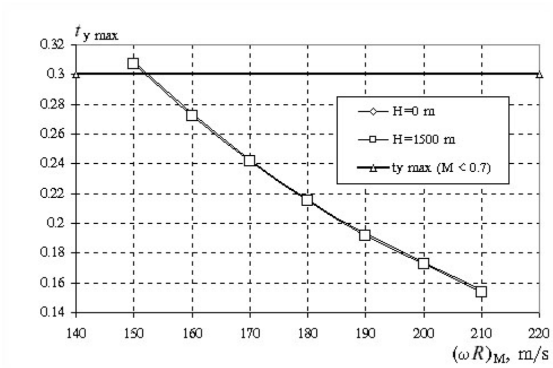


Fig. 10. Main Rotor Thrust Coefficient t_y versus Main Rotor Blade Tip Speed $(\omega R)_M$.

The second condition was analysed for three values of i_M providing the blade tip speeds of 195, 200 and 205 m/s at $n_{E\ \text{take-off}}$= 2,700 rpm. It was assumed that helicopter would cruise at reduced main rotor speeds corresponding to $n_{E\ cr}$ = 2,400 rpm. Fig. 11 shows $(\omega R)_M$ versus n_E, i_M.

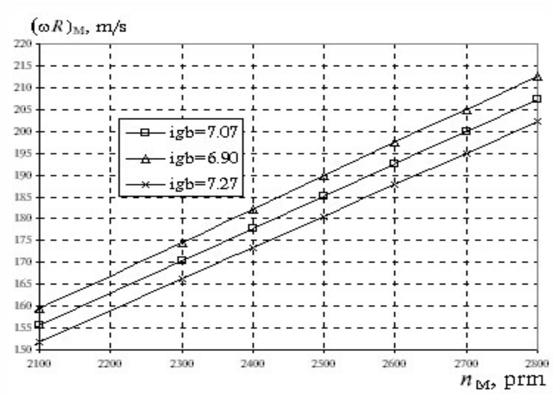


Fig. 11. Main Rotor Blade Tip Speed $(\omega R)_M$ versus Engine RPM and Main Gear Box Reduction Ratio i_M.

The economic speed V_{ee} corresponding to the minimal required power was determined for each blade tip speed value. Within the blade tip speed range of 195-205 m/s the economic speed varies within a narrow range of 95-105 km/h, therefore V_{ee} = 100 km/h was assumed for all $(\omega R)_M$ values. At this speed for ISA, SL the helicopter gross weight providing a 7.5 m/s rate of climb with one engine operating at the take-off power rating determined by of the external characteristic was defined.

The Category A helicopter gross weight-versus-blade tip speed and main gear box reduction ratio curve was obtained from the analysis results (Fig. 12). Here each value of the blade tip speed determines its own value of the engine power in terms of the external characteristic.

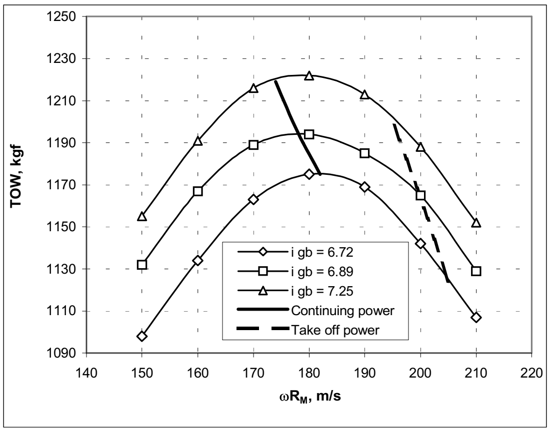


Fig. 12. Helicopter Gross Weight G_{V_y} at Economic Speed versus Blade Tip Speed $(\omega R)_M$ and Main Gear Box Reduction Ratio i_M.

The diagram shows that the optimal blade tip speed providing the Category A helicopter gross weight is ~180 m/s and is very little affected by the reduction ratio. The maximum value of the helicopter gross weight, i.e. 1,222 kgf, is obtained at the reduction ratio equal to 7.25 which corresponds to the tip speed equal to 195 m/s at the engine crankshaft speed of 2,700 rpm.

An important advantage of the power plant comprising two piston engines is as follows: if one engine fails it is not necessary to increase the power of the other engine to the take-off power rating. Table 2 gives engine power values (with due account of the power bleed for the fan drive) required for helicopter flight at a speed V_{ee} for three values of $(\omega R)_M$ and fixed gear ratio i_M=6.89.

Table 2

Required Power in Economic Flight Condition

$(\omega R)_M$, m/s	160	180	200
$N_{ев}$, hp	105	118	130

It can be seen that for all $(\omega R)_M$ values the required power does not exceed the take-off power of one engine. Therefore, when one engine fails in cruise, it is sufficient for the other engine to reach its external characteristic; to do this, it is necessary to open the throttle plate completely. Further, is has been shown that piston engines have a short acceleration time, and with one engine inoperative the other will achieve the optimal power rating quite fast.

Fig. 12 shows curves corresponding to the engine take-off and cruising power ratings. At the gear ratio i_M=7.25 the cruising power rating of the operating engine will provide helicopter operation in Category A with a take-off weight of 1,200 kgf.

Thus, for take-off weight of 1,200 kgf the gear ratio i_M=7.25 can provide hover out of ground effect and flight in Category A close to the optimal ones. In hover $(\omega R)_M$=195 m/s can provide maximum take-off weight of 1,400 kgf (ISA, SL) and hover ceiling of 1,500 m for a take-off weight of 1,200 kgf.

4. Studies of Engine Failures in Hover

One of the advantages of any twin engine helicopter is its capability to perform safe continued flight and landing when one engine fails. In this case it is of utmost importance to consider dynamics of the "rotors-engines" system from the point of view of calculating the time required for the pilot for actions after one engine failure. To study transitions, one engine failures in vertical flight conditions (i.e. hover, climbout, power-on descent and autorotation) were studied.

The helicopter was considered as a material mass point m_{TO} moving vertically at a speed V_y at an altitude H above the ground under the influence of the main rotor thrust T_M. The equation expressing the helicopter motion is as follows:

$$T_M - m_{TO}g = dV_y/dt,\ dH/dt = V_y. \qquad (9)$$

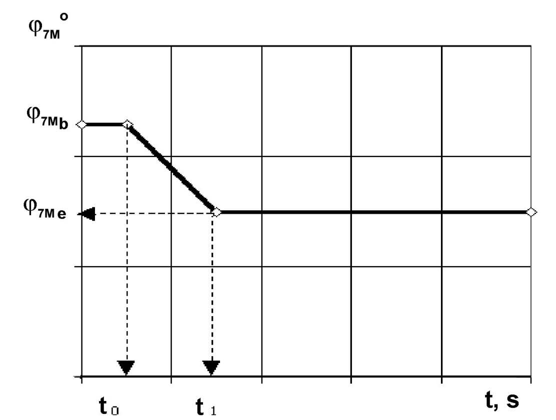


Fig. 13. Main Rotor Collective Pitch Control Law

The pilot control action is carried out as collective pitch control lever displacement $\varphi_{7M} = \varphi_{7M}(t)$ and engine throttling level $\chi_E = \chi_E\,(t)$.

$$\varphi_{7M}(t) = \begin{cases} \varphi_{7M\,b} & t < t_0 \\ \varphi_{7M\,b} + \dfrac{\varphi_{7M\,b} - \varphi_{7M\,e}}{t_1 - t_0}(t - t_0), \quad if & t_0 < t < t_1 \\ \varphi_{7M\,e} & t > t_1 \end{cases} \qquad (10)$$

Fig. 13 shows a typical time history of the main rotor collective pitch φ_{7M} versus ($\varphi_{7M\,b}$ - $\varphi_{7M\,e}$). Parameters t_0 и t_1 determine the pilot control action delay and gradient.

The level of the engine throttling χ_e is determined by the main rotor pitch control lever position and the throttle control twist grip:

$$\chi_E = \chi_M\,(\varphi_{7M}) + \Delta\chi(t), \qquad (11)$$

where χ_M is the collective pitch-throttle relation taking into account the throttling level determined by the main rotor collective pitch; $\Delta\chi$ is the throttle lever displacement produced by the pilot.

$$\chi_M = \begin{cases} \chi_{M\min} \\ \chi_{M\min} + \dfrac{\chi_{M\max} - \chi_{M\min}}{\varphi_{M\max} - \varphi_{M\min}}(\varphi_{7M} - \varphi_{M\min}), \\ \chi_{M\max} \end{cases} \qquad (12)$$

$$if \quad \begin{array}{|c} \varphi_{7M} < \varphi_{M\min} \\ \varphi_{M\min} < \varphi_{7M} < \varphi_{M\max} \\ \varphi_{7M} > \varphi_{M\max} \end{array}$$

Fig. 14 shows the collective pitch-throttle relation used in the analysis.

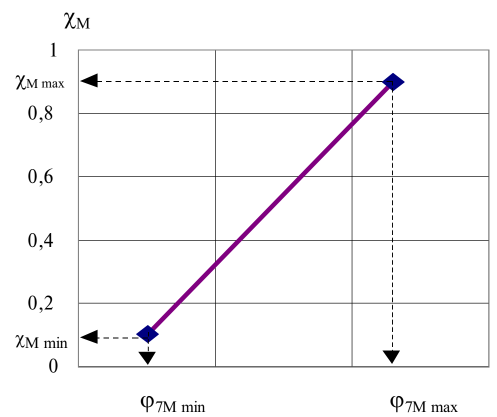


Fig. 14. Collective Pitch-Throttle Relation.

As the engine throttling level varies within $0<\chi_e<1$, the throttle lever displacement is limited by the upper and lower limits $\Delta\chi_{max}$ and $\Delta\chi_{min}$ respectively in accordance with Equation (11)

$$\Delta\chi_{min} < \Delta\chi(t) < \Delta\chi_{max}, \qquad (13)$$

where

$$\Delta\chi_{min} = -\chi_E\,[\varphi_{7M}(t)],\ \Delta\chi_{max} = 1 - \chi_E\,[\varphi_{7M}(t)].$$

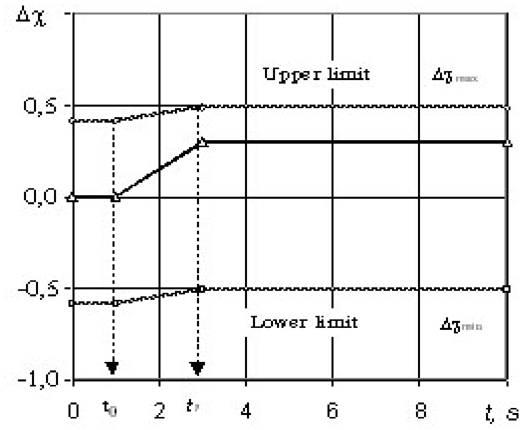


Fig. 15. Range Limits and Throttle Lever Displacement Relation.

Fig. 15 presents the upper and lower limits of the throttle lever displacement in accordance with relation (13) and an exemplary nature of the throttle lever displacement which in the general case can be described by the following relation:

$$\Delta\chi(t) = \begin{cases} \Delta\chi_{\min} \\ \Delta\chi_{\min} + \dfrac{\Delta\chi_{\max} - \Delta\chi_{\min}}{t_1 - t_0}(t - t_0), \\ \Delta\chi_{\max} \end{cases} \quad (14)$$

$$\text{if} \quad \begin{vmatrix} t < t_0 \\ t_0 < t < t_1 \\ t > t_1 \end{vmatrix}$$

The system of linear differential equations (9), (3) containing variable non-linear coefficients from relations (10)-(14) and tabular functions (Figs. 5,7,8) is solved numerically relative to variables H, V_y and ω_e. The helicopter trim in hover is considered to be the initial condition for solving the above equation:

$$T_M = mg,\ V_y = 0,\ \omega_{e0} = i_M\,(\omega R)_{M0}/R_M.$$

Let us consider the case of one engine failure and possible ways out of the situation. The helicopter has the following parameters:

<u>Helicopter:</u> m_{TO}=1,000 kg; L_T=4.8 m; ??= 0.965; k_e=1.
<u>Main rotor:</u> R_M = 5 m; J_M = 97.9 kgf/m^2; i_M = 5.215.
<u>Tail rotor:</u> R_T=0.6 m; J_T = 0.069 kgf/m^2; i_T = 0. 63.
<u>Hover:</u> H=200 m; $(\omega R)_{M0}$=210 m/s.

By introducing main rotor collective pitch and throttle lever control relations (10) and (11) respectively, we assume that the time delay t_0 is 1 s in both cases, and the period of the control action Δt is equal to $t_1 - t_0 = 2$ s irrespective of its absolute value.

Fig. 16 illustrates the case when after engine failure the collective pitch is not changed by the pilot, and the throttle lever is displaced up to the limit of travel with the engine operating without turbocharging. During the first two seconds the operative engine rpm drop so that the blade tip speed decreases to 165 m/s, and the main rotor thrust becomes twice lower. The helicopter starts descending, and in 4 seconds the rate of descent increases up to 12 m/s. When the throttle lever is displaced to the limit of travel, the tip speed increases up to 220 m/s, and the rate of descent slightly decreases up to 11 m/s. The helicopter enters the steady power-on descent. The altitude loss during 10 seconds is 95m.

If the second operating engine is turbocharged and the throttle lever is displaced to the limit of travel, no cardinal changes occur in the steady power-on descent. Due a steeper gradient of the engine torque-versus-rpm relation the steady main rotor operating condition moves to lower speed which in the end results in the blade tip speed of 190 m/s and rate of descent equal to ~ 11.6 m/s.

To achieve higher speeds, it is necessary to decrease the main rotor pitch and move the throttle lever to the limit of travel. Fig. 17 shows the results obtained from decreasing the pitch angle up to 7°. In this case the engine achieves the maximum speed at the maximum power developed which provides the blade tip speed of 220 m/s and rate of descent equal to ~ 10.6 m/s. The helicopter achieves the steady descent condition within 8 seconds with an altitude loss of 70-80 m.

Thus, the analysis shows that when one engine fails in hover, the main rotor can achieve the design rpm within 6-8 seconds by a small decrease of the main rotor pitch and moving the throttle lever to the limit of travel. After that the pilot can perform slant descent or level forward flight at speeds 50-100 km/h to make a safe running landing or pulling up.

5. Dangerous H-V Areas for Single- and Twin- Engine Helicopter

When helicopters operate in cities, they have to use steep take-off and landing paths due to the limited air space. Engine failures along the above paths can result in grave incidents and accidents endangering the lives not only of the occupants, but also those present in the take-off and landing areas. The twin-engine power plant will allow the helicopter not only to continue taking off but to fly to destination or to perform a safe landing to the take-off site if one engine fails during take-off.

To model engine failure in climb, a non-linear mathematical model of helicopter longitudinal movement was used, and at each integration step the main rotor forces and moments were calculated. The helicopter airframe aerodynamic performance obtained from the model tests in the MAI T-1 wind tunnel [4] and the *M-332A* engine external characteristic were used in the analysis (Fig. 5). The following limitations were assumed in modelling landings:

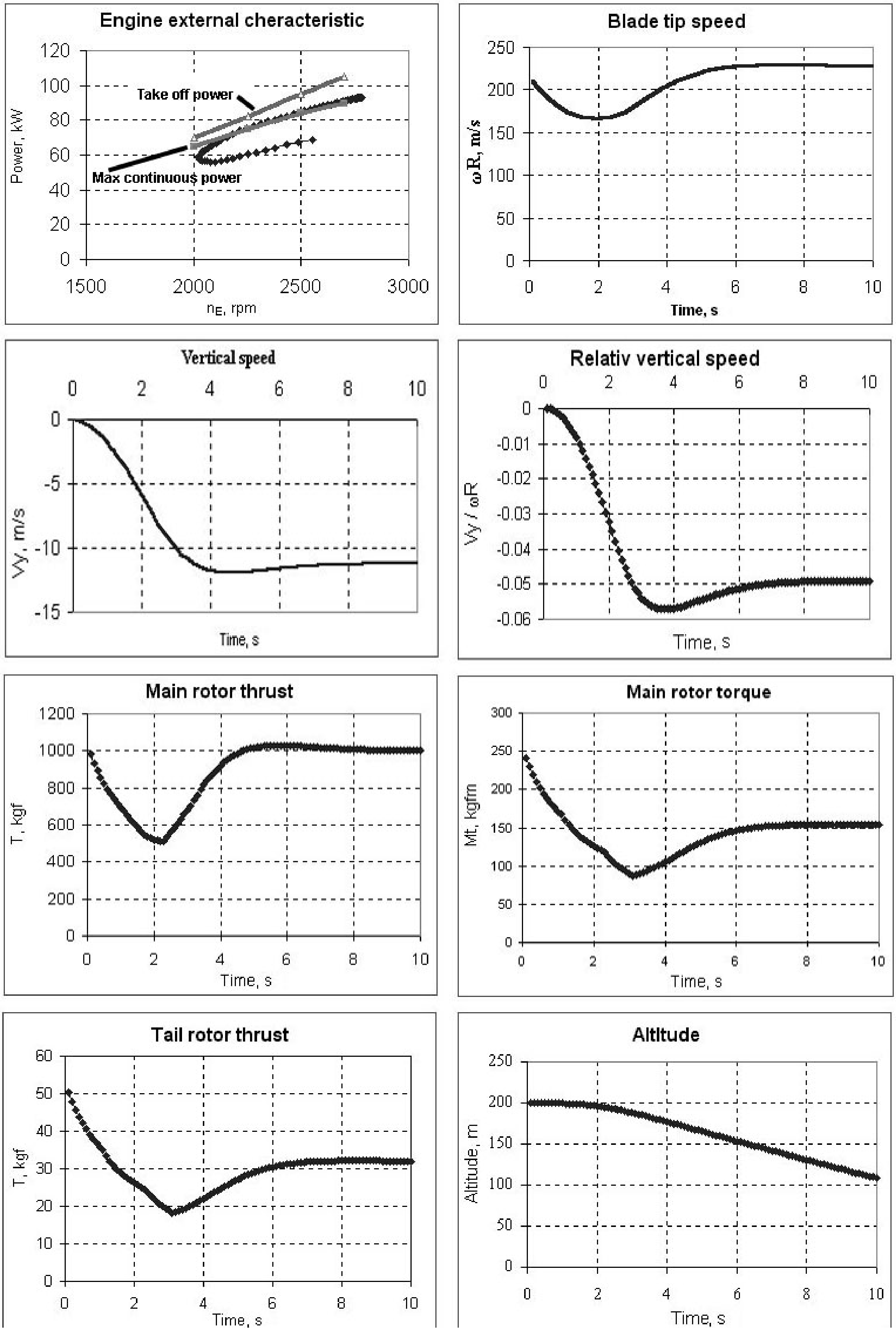


Fig.16. Helicopter Descent with One Engine Inoperative without Blade Tip Speed Loss.

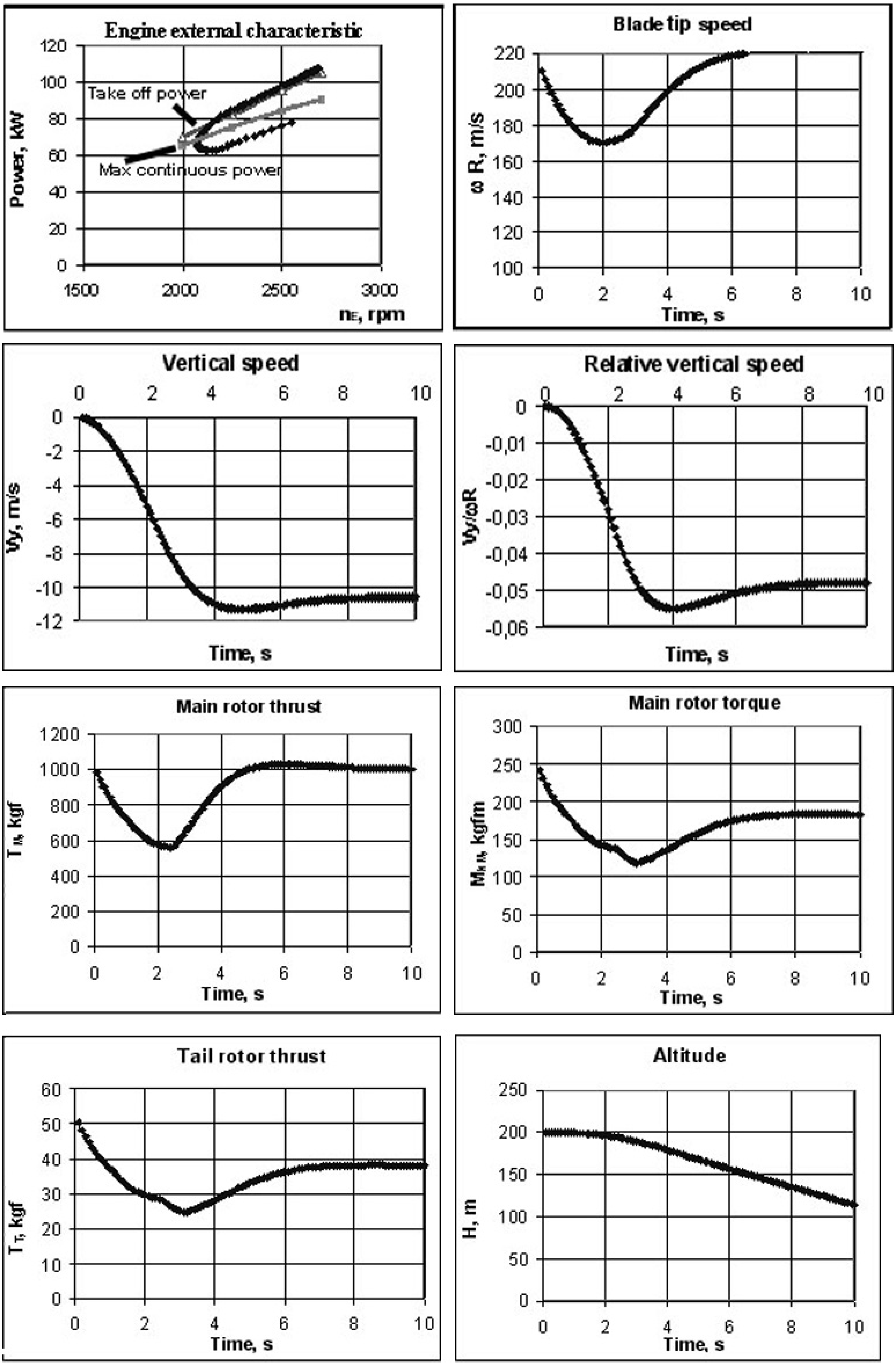


Fig.17. Helicopter Descent with One Engine Inoperative with Blade Tip Speed Loss and Turbocharging.

1. The maximum horizontal component of the landing speed is equal to 20 km/h, the landing angle of pitch is ≤9°.
2. The maximum rate of descent is 2 m/s.
3. To avoid the vortex ring area in the speed range from 0 to 40 km/h, the rate of descent does not exceed 4 m/s.
5. The delay in the pilot control action in hover and low-speed flight is 0.5 s, and in flight at speeds exceeding the economic speed, 1 s.
5. The intermediate approach safe altitude is assumed to be 5 m.

In modelling the engine external characteristic it was assumed that the engine failed loses its power immediately. The other operating engine automatically attains the higher power rating in 0.5 s as a result of the throttle lever displacement.
To compare the single- and twin-engine helicopter take-off and landing performance, the H-V dangerous area boundaries were calculated for the *Mi-60 MAI* helicopter with one and both engines failed. It should be noted that the latter case is equivalent to failure of the only engine powering the single-engine helicopter whose other parameters are identical to those of the twin-engine helicopter.
The diagrams of the dangerous H-V area design boundaries presented in Fig. 18 show that the availability of two engines allow the *Mi-60 MAI* helicopter to widen greatly the capabilities of safe operation in take-off and landing. The statistics show that 85% of the total helicopter accidents happen under these conditions.

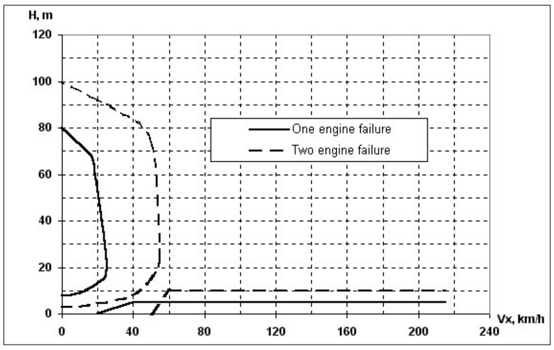


Fig. 18. Boundaries of Helicopter Dangerous H-V Areas.

The lower boundary of the left dangerous H-V area is determined by engine failure in hover or low-level flight. As it can be seen from the diagrams, when one engine fails the safe hover altitude of the helicopter is 8 m, but when both engines fail, it is only 3 m. When the airspeed increases, the lower boundary of the left area increases up to 15-20 m. In this case the horizontal velocity components will be ~20 km/h and 50 km/h for one and two engine failure respectively. Below this boundary the landing parameters of the helicopter do not exceed the prescribed limitations provided the altitude at which the helicopter is pulled up, is reasonably selected, and the helicopter can make a safe landing.

The parameters obtained for the lower boundary of the left dangerous H-V area show that the take-off and landing path for twin-engine helicopters can be approximately 4 times steeper than that of single-engine helicopters, it means that the twin-engine helicopter can operate in cities.
The upper boundary of the left dangerous H-V area is determined by the helicopter possibility to land from a relatively high altitude, it is limited by the altitude loss during the helicopter acceleration required to reach the safety speed. The above boundary position depends on the helicopter acceleration rate: the higher the nose-down pitch is, the lesser the altitude loss is. This makes the piloting technique more complicated, therefore in modelling the average acceleration rate with $\Delta \upsilon \sim 15°$ was selected. The diagram in Fig. 18 shows that the single-engine helicopter safety hover altitude is 100 m which is 20 m higher than that of the twin-engine helicopter in case one engine fails.
The upper boundary of the right dangerous H-V area was determined from the conditions required to provide the altitude sufficient for the helicopter to decelerate up to the maximum allowable landing speed and minimum safety altitude of the helicopter flyover above the ground surface (caused by the tail boom approach to the ground in nose-up pitch). The analysis has shown that for the helicopter under consideration this boundary is determined only by the safety altitude of flyover above the ground, which, depending upon the pitch, is 2.0-2.5 m. For the single-engine helicopter the safety altitude boundary is not less than 10 m. In addition, the boundary of the right dangerous V-H area in terms of speed is 25 km/h and 55 km/h for the twin- and single-engine helicopters respectively.
Thus, the modelling of one or two engine failures has demonstrated that the *Mi-60 MAI* helicopter powered by two engines will have much more superior take-off and landing performance as compared to those inherent in helicopters in the same weight category but powered by a single engine.

6. References

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