Dynamic engine charge simulation for unmanned aerial vehicles

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Abstract. Rational use of wave processes of significant intensity in the intake pipes of piston engines allows providing dynamic charge, which leads to a noticeable increase in engine power, reduction of fuel consumption. This is especially true for engines used on unmanned aerial vehicles. For numerical calculation of the dynamic charge, a modification of the method of decay of an arbitrary discontinuity has been developed, based on the application of special gas-dynamic functions of the unsteady flow, which does not use a simplifying linearization and thus provides increased accuracy of the results required for wave processes of significant intensity. Corresponding calculations of the engine cylinder charge filling at dynamic charge have shown the possibility of the power increase by 24%, which corresponds well with the experimental data.

1. Introduction
The periodic behavior of the working processes in the piston engine cylinders is the cause of vibrational dynamic phenomena in their gas-air paths. This phenomenon can be used for significant improvement of the main parameters of the engines, like power and fuel efficiency [1-3]. In this case, the inlet manifolds are adjusted for dynamic charge, i.e. the length and section of the individual manifolds for each of the engine cylinders are chosen. At the beginning of the inlet into the cylinder in front of the valve, a vacuum is formed, and decompression wave is transmitted to the open end of the inlet manifold, where it is reflected by a compression wave. Selection of the geometry of the individual manifolds allows ensuring that the compression wave arrives to the cylinder at the most favorable moment before closing the valve. This leads to a significant increase of the volumetric coefficient $\eta_v$ and, consequently, the power by 10-20% [4-6] and improves engine fuel efficiency by 5-10% [2, 7, 8].

Engine power increase together with simultaneous increase of the volumetric coefficient is especially important for the piston engines installed on unmanned aerial vehicles (UAVs) of various applications, as it will provide increase of flight characteristics, increase of a flight time. At the same time, there is a tendency to use diesel engines fueled by kerosene as the most economical ones for the mid-range UAVs.
Numerical methods of gas dynamics simulation tasks are now widely used for calculations of unsteady gas-dynamic processes [9-11]. The numerical method of the decay of an arbitrary discontinuity (DAD) – method of Godunov is the most effective for calculation of the dynamic charge in extended inlet manifolds in a one-dimensional simulation [1, 12, 13]. The ideal gas flow \( p = \rho RT \) in coordinates "length-time", \( x - t \) is described by the system of basic equations of gas dynamics [1, 11, 14]:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} &= 0, \\
\frac{\partial \rho u}{\partial t} + \frac{\partial (\rho u^2 + p)}{\partial x} &= -\frac{\rho u}{D} \frac{\partial D}{\partial x}, \\
\frac{\partial \rho e}{\partial t} + \frac{\partial (\rho e u + p u)}{\partial x} &= -\frac{\rho}{D} \frac{\partial D}{\partial x} \frac{\partial (\rho u^2 + p)}{\partial x} + \frac{\partial \nu}{\partial x} \frac{\partial u}{\partial x} + \frac{\partial \alpha}{\partial x} \frac{\partial T}{\partial x}.
\end{align*}
\]

(1)

where, \( \rho \), \( u \), \( p \), \( T \), \( e \) – density, speed, pressure, temperature, specific internal energy \( (e=c_vT) \); \( D \) and \( T_c \) – hydraulic diameter and local pipe wall temperature; \( \lambda \), \( \alpha \) – friction and heat transfer coefficients. Numerical implementation of the method after dividing the calculation area into segments (cells) \( \Delta x \) most often uses simplified dependencies (linearization) [12-14] for speeds \( u_{i+1/2} \) and pressure \( p_{i+0.5} \), with them the flow crosses the border \( i+0.5 \) between the cells \( i \) and \( i+1 \) (figure 1):

\[
\begin{align*}
\rho_{i+0.5} &= \rho_{i+1} + \alpha \rho (u_{i+1/2} - u_{i}), \\
p_{i+0.5} &= p_{i+1} - \alpha \rho (u_{i+1} - u_{i+0.5}).
\end{align*}
\]

Figure 1. Decay of an arbitrary discontinuity (DAD) on the boundary between the cells of the numerical calculation.

The presented relations are obtained from finite-difference recording of the conditions of preservation of Riemann's invariants at transitions through the fronts of elementary waves, respectively \( r^+ \) - backwards and \( r^- \) - straightforward with an equal speed \( u_{i+0.5} = u_w \) and pressure \( p_{i+0.5} = p_w \) on either side of the contact surface that separates the zones \( i+0.5 \) and \( w \) behind the wave fronts after the DAD. After the determination \( u_{i+0.5} \), \( p_{i+0.5} \) and the corresponding density \( \rho_{i+0.5} \) we calculate mass, pulse and total enthalpy fluxes across the boundary \( i+0.5 \), which allows us to move to the final stage of the calculation scheme in accordance with the system (1). Unfortunately, the use of linearized relations in the DAD method gives satisfactory calculation results only for wave processes with insignificant amplitudes [11, 12, 14]. At dynamic charging in front of the valve, the wave amplitudes can reach 0.5 Bar, and such algorithm does not provide the necessary accuracy of the results even with a significant reduction of the calculation step \( \Delta t \). For modeling of such processes it is recommended to use the classical scheme of the decay of discontinuity method, taking into account the shock fronts [11, 12, 14]. However, the algorithm of such a scheme is heterogeneous, logically complex and requires iterations at each calculation step.
2. Description of the research

The paper presents a new modification of the DAD method, based on the usage of simple Riemann waves without simplifying linearization for both - compression front and the depression front. A Ferri [15] showed that the replacement in the calculations of shock waves by simple waves of Riemann within the amplitudes of compression 0.5 Bar was justified and provided the same accuracy of the results. In this paper, it was proposed to use specially developed non-stationary gas-dynamic functions (NSGDF) from the Mach number 

\[ M = \frac{u}{a} \]

to express the differences at the fronts of these waves [1, 16].

To cross the front of the backward wave, we have:

\[ r^- = \frac{2}{k-1} a + u = \frac{2}{k-1} a'' \]

where \( a'' \) - sound speed if the stream is slowed down by the wave \((u = 0)\). Obviously, the speed \( a'' \) is unambiguously related to the value of Riemann's invariant \( r^+ \), as well as the corresponding temperature \( \rho^+ \), density \( \rho^+ \) and pressure \( p^+ \). Then, for the difference in sound speed, temperature, density and pressure at the front of the wave going against the flow, it is possible to set the following equations:

\[
\begin{align*}
\alpha_i(M_i) &= a_i \alpha''(M_{i+0.5}) = a_i \alpha''(M_i), & T_i &= T_i + \tau''(M_{i+0.5}) = T_i \frac{\tau''(M_{i+0.5})}{\tau''(M_i)}, \\
\rho_i &= \rho'' \rho''(M_{i+0.5}) = \rho_i \frac{\rho''(M_{i+0.5})}{\rho''(M_i)}, & p_i &= \rho_i \frac{p''(M_{i+0.5})}{p''(M_i)} = p_i \frac{\pi''(M_{i+0.5})}{\pi''(M_i)},
\end{align*}
\]

where, the NSGDF \( \alpha'(M) = \left(1 + \frac{k-1}{2} M\right)^{-1} \), \( \tau''(M) = \left[\alpha''(M)\right]^{2k}, \) \( \rho'' \) and \( \rho'' \) are present as follows:

\[
\begin{align*}
\alpha''(M) &= \left(1 + \frac{k-1}{2} M\right)^{-1} \cdot \tau''(M) = \left[\alpha''(M)\right]^{2k}, & \pi''(M) &= \left[\alpha''(M)\right]^{2k}.
\end{align*}
\]

Obviously, to cross the front of the forward wave in the flow, \( r^- = \frac{2}{k-1} a - u = \frac{2}{k-1} a'' \), where \( a'' \) - sound speed when the wave is slowing down. The corresponding variations in sound speed, temperature, density and pressure at the front of this wave can be expressed as:

\[
\begin{align*}
\alpha_w &= a_i \alpha'' \alpha'(M_i) = a_i \alpha''(M_i), & T_w &= T_i + \tau''(M_{i+1}) = T_i \frac{\tau''(M_{i+1})}{\tau''(M_i)}, \\
\rho_w &= \rho_i \rho'' \rho'(M_{i+1}) = \rho_i \frac{\rho''(M_{i+1})}{\rho''(M_{i+1})}, & p_w &= \rho_i \frac{p''(M_{i+1})}{p''(M_{i+1})} = \rho_i \frac{\pi''(M_{i+1})}{\pi''(M_{i+1})},
\end{align*}
\]

where, the NSGDF \( \alpha'(M) = \left(1 - \frac{k-1}{2} M\right)^{-1} \), \( \tau'(M) = \left[\alpha'(M)\right]^{2k}, \) \( \rho'(M) = \left[\alpha'(M)\right]^{2k} \) and \( \pi'(M) = \left[\alpha'(M)\right]^{2k} \).

Apparently, on the contact surface \( p_{i+0.5} = p_w \), and for pressure drops between the wave configuration zones we have:
speed parity \( u_{i+0.5} = M_{i+0.5}a_{i+0.5} = u_w = M_w a_w \) lets us to record the following:

\[
M_{i+0.5}a_i = M_w a_{i+1} \frac{\alpha'(M_w)}{\alpha'(M_{i+1})}.
\]

Using the formulas \( F = \frac{\alpha'(M_{i+1})}{\alpha'(M_i)} \), \( X = F \left( \frac{p}{p_{i+1}} \right)^{\frac{k-1}{2k}} \) and \( Y = F \frac{a_i}{a_{i+1}} \), containing the initial parameters \( p_i, p_{i+1}, a_i, a_{i+1}, M_i, M_{i+1} \), by revealing the record \( \alpha'(M), \alpha'(M) \) from \( M \) and performing transformations of the system of equations (2) and (3), it is possible to obtain simple expressions of the Mach numbers \( M \):

\[
M_{i+0.5} = \frac{2 X - 1}{k - 1 Y + 1},
\]

\[
M_w = \frac{Y}{X} M_{i+0.5}.
\]

To identify flows over the border \( i+0.5 \) it only takes \( M_{i+0.5} \). NSGDF calculates the corresponding \( p_{i+0.5}, p_{i+1}, M_{i+1} \), then flow rate, impulse and full enthalpy.

Undoubtedly advantages of the use of NSGDF are shown in the calculations at the boundaries of the calculation areas with a one-dimensional non-stationary flow, which ends in some of the local resistances (LR) considered as concentrated boundary conditions (BC) [1]. Calculation methods for the stationary flow of compressible gas through such elements are based on gas-dynamic functions [17] from the \( M \) - number or the speed limit \( \lambda = u/\alpha_c \), where \( \alpha_c \) – critical speed of sound. When developing models of interaction of non-stationary flow with such BC, it is necessary to use the notion of DAD. Here, NSGDFs are used in combination with known gas-dynamic functions of the stationary flow since every calculated step of the DAD uses the notion of a quasi-stationary flow between the waves that passed and reflected from BC [3, 15, 18].

Let us imagine the calculation model of interaction of a non-stationary flow with the BC "inlet valve" in the adjusted inlet manifolds at dynamic engine charge. The DAD scheme for the design step is shown in figure 2. The parameters known before the DAD are \( p_m, M_m \) in the last cell of the calculation area, the current value of the valve slot passage area \( F_v \) and the pressure in the cylinder \( p_c \). The index \( m + 0.5 \) indicates the parameters in the manifold behind the edge of the reflected wave required to calculate the mass flows, pulse and total enthalpy across the conditional.

The pressure difference between the DAD zones can be recorded in the form of stationary and non-stationary functions:

\[
\frac{P_m}{p_v} = \frac{P_{m+0.5}}{p_v} \frac{\pi^*(M_m)\pi(M_{m+0.5})}{\pi^*(M_{m+0.5})\pi(M_v)}.
\]
Figure 2. Scheme for calculating the DAD when flowing into the cylinder through the valve.

For quasi-stationary flow between zones \( m + 0.5 \) and out of the valve slot \( v \) the rightly known expenditure ratio [17]:

\[
F_m P_{m+0.5} (T_{m+0.5})^{-1} q(M_{m+0.5}) = \mu F_v P_v (T_v)^{-1} q(M_v)
\]

(7)

Where \( \pi(M) = \left(1 + \frac{k-1}{2} M^2\right)^{\frac{k-1}{k}} \),

\[
q(M) = M^{\frac{2}{k+1}} \left(1 + \frac{k-1}{2} M^2\right)^{-\frac{k-1}{k}}
\]

is stationary gas-dynamic functions [17]. To consider the unevenness of the flow in the section \( F_v \) the valve slot has a flow coefficient \( \mu \), which is pre-determined by purging the valve. Air flow through the valve in the engine cylinder head is not accompanied by heat exchange and is assumed to be adiabatic. Then for stationary braking temperature we have:

\[
M_v F_v = 1
\]

in addition, it is known from the experiments that the total pressure losses in the short channels with restricted flow section, which is the inlet nozzle in the valve head, are negligibly small, i.e. \( P_{m+0.5} = P_v^* \). As a result, from (7) regarding the designation \( f \) we have:

\[
q(M_{m+0.5}) = f q(M_v)
\]

(8)

Flow into the cylinder can be pre-critical or critical, with flow locked in the valve slot. In pre-critical flow, the pressure at the valve slot exit is obviously \( P_v \) equals the pressure in the cylinder \( P_c \). In critical mode \( P_v \) is determined by the condition \( M_v = 1 \).

At the time of \( M_v = 1 \) from (8) you get the ratio, which for this \( f \) allows you to determine the value \( M_{m+0.5,cr} \) in the area of \( m+0.5 \) in critical mode:

\[
q(M_{m+0.5,cr}) = \hat{f}
\]

(9)

Now, by setting up \( M_v = 1 \) and \( M_{m+0.5,cr} \) into (6), you can find the maximum difference \( \left(P_{m} P_{c}^{-1}\right)_{\hat{f}} \). If, in the calculated step \( P_{m} P_{c}^{-1} \geq \left(P_{m} P_{c}^{-1}\right)_{\hat{f}} \), then we have a critical flow mode with locking at the valve slot outlet, and the number required to calculate the DAD number \( M_{m+0.5,cr} \) thus defined. At the same time \( P_{m} P_{c}^{-1} = \left(P_{m} P_{c}^{-1}\right)_{\hat{f}} \) and obviously, the pressure at the valve slot exit of the \( P_v \) will be greater than the \( P_c \). If that assessment turns out to be \( P_{m} P_{c}^{-1} < \left(P_{m} P_{c}^{-1}\right)_{\hat{f}} \), the regime is pre-critical. The pressure at the outlet of the valve slot is equal to the pressure in the cylinder, and in equation (6) instead of \( P_v \) it is necessary to substitute the pressure \( P_c \) known at this design step. In this mode, the system of equations (6) and (8) with
two unknowns $M_{m=0.5}$ and $M_{n}$, is solved by iteration. Number $M_{m=0.5}$ necessary to calculate the wave process in the manifold and the flow into the cylinder. To describe the process in the cylinder, the technique described in [19] is used.

3. Results of calculations

In accordance with the above described, the wave process simulation for dynamic charge was performed for diesel engine 1Ch8.5/11 (One cylinder four tact diesel engine, Bore 85 mm, Stroke 110 mm), which can serve as a prototype for the development of the aviation diesel engine for UAV. General design parameters of this engine are: speed $n = 1500$ rpm (revolutions per minute), volumetric coefficient $\eta_v = 0.85$ in the absence of dynamic charge have been used as the input data. In work [8] classical experimental results on research of dynamic charge of this motor are presented. Figure 3 shows obtained in the calculation and published experiment [8], showing dependence of $\mu_v$ on the length of the inlet manifold $L$.

The calculated results are well consistent with the experimental data in both qualitative and quantitative terms. Here is shown the wave character of the change of $\eta_v$ along the length of the tube, caused by the number of periods of free oscillations, with full phase coordination with the experiment. In the maximum area for dynamic boost, the $\eta_v$ calculation error is no more than 1.5%. It is also shown that dynamic boost can provide an increase in $\eta_v$ above 1.05. Compared to a non-configured system, the volumetric coefficient, and therefore the engine power, which is proportional to $\eta_v$, increases by 24%.

![Figure 3. Dependence of the volumetric coefficient $\eta_v$ on the length $L$ of the adjusted pipe by calculations results and experiment description in [8].](image)

Note that when using a propeller unit with a propeller screw, extended inlet pipes can be placed along the drone fuselage with a forward flow inlet opening, that will provide an additional 5-8% increase in $\eta_v$ and capacity due to the high-speed head.

4. Conclusion

The paper presents the results of numerical simulation of the dynamic charge for piston engine, which can be used as a prototype engine for UAV. It has been shown that such charge can significantly increase the engine power. It is important to note that the simulation was carried out based on a new modification of the numerical method of DAD, which uses special non-stationary gas-dynamic functions from the Mach number, expressing the differences in parameters at the fronts of simple Riemann waves. Here we obtain a simple homogeneous computational algorithm that does not require iterations at the computational step,
caused by the extraction of the shock front, as it takes place in the classic Godunov scheme for the wave processes of significant amplitude. In addition, the use of Mach numbers allows us to conveniently express the calculated relations at the boundaries, in particular, at the valve and the inlet to the manifold.

Comparison of the simulation results carried out by means of a new modification of the DAD method with experimental data of well-known authors, testifies the adequacy of the proposed method. It can be recommended for solving practical problems of gas dynamics with wave processes of significant intensity. In particular, when designing the inlet manifolds of piston engines with adjustment of the dynamic charge with considerable increase in power.

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