Application of Torsional Dampers for the Vibrations Reduction in Crankshafts of Piston Aircraft Engines

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Abstract. It is a well-known fact that piston engines shake, among which some of them more than others. Therefore, such type of vibrations, created by piston engines, should be controlled somehow. For the reduction of torsional crankshaft vibrations, torsional dampers are often used. The crankshaft vibrations are intrinsic in any internal combustion engine because of the powerful though unequal forces, which act directly on its crankshaft. Although the dampers will not add engine horsepower, lack of using them causes that crankshaft vibrations will hamper the horsepower potential of engines. The study attempts to explore how torsional-vibration damping methods can be improved for traditional aircraft horizontally-opposed engines.

1 Introduction

In the case of popular light-planes, the piston-engines are still doing as the primary propulsion-sources. A significant amount of horizontally opposed piston engines powers American light planes. In the case of popular light-planes, the piston-engines are still doing as the primary propulsion-sources. A significant amount of horizontally opposed piston engines powers American light planes. In most cases, Continental, Lycoming, and Franklin manufactured them. These engines have their counterparts, albeit in a significantly smaller quantity, in Europe[1]. Every one of the opposed-type engines has a crankshaft positioned in the centre between two banks of cylinders situated directly opposite each other. Thus, the pistons of both cylinder banks are put together with the single crankshaft by connecting rods. Although the opposed-type engines can be either liquid-cooled or air-cooled, their air-cooled version, with the cylinders moving in the horizontal position, is utilized primarily in aviation. Their key advantages are low vibration characteristics and a low weight-to-horsepower ratio. In twin-engine applications, their narrow silhouettes facilitate assembly in the horizontal position on the wings of airplanes.Approved designations for the opposed-

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type engines are: (first) the designation with the letter 'O' and a dash followed by the piston displacement, and (second) the designation without a prefix before the 'O' for engines of recommended crankshafts' setups in the horizontal position. For example, the 'O-360' specifies the opposed-engine with 360 cubic-inches of displacement. The work position of crankshafts of the opposed-type engines is vertical when the letter 'V' precedes the letter 'O' (e.g., VO-360). The vertical position is characteristic for the first generations of helicopters, driven by reciprocated engines.Other complementary designations for the opposed-type engines are the following: (i) engine is with a fuel-injected system when the letter 'I' precedes the letter 'O' such as IO-360, (ii) an engine has a turbo-supercharging system when one of prefixes 'T' or 'TS' precedes the mark 'O', which occurs in its designation, (iii) a geared engine is denoted by the prefix 'G' in its designation, and (iv) an engine has left-hand rotation as considering the view from the engine rear looking forward when the prefix 'L' is used.

In this work, selected torsional-vibration damping methods are analyzed to reduce torsional vibrations in air-cooled and horizontally-opposed piston engines manufactured by Franklin Aircraft Engines. The origin of this firm is affiliated with the H.H. Franklin Company. In 1902 the H.H. Franklin Company begun manufacturing Franklin air-cooled automobiles in Syracuse (New York, USA). In 1937 this company was purchased by a group of ex-employees and changed its name to the Aircooled Motors Development Company. This company was continuing to market its engines under the Franklin name [2]. Until 2002 the Polish production of Franklin engines had been continuing in Rzeszów by the WSK-PZL firm. In 2002 a Polish group headed by Roman Sadowski took over certificates and tools owned by the WSK-PZL firm to manufacture the Franklin piston engines.This group has formed the firm of Franklin Aircraft Engines in the city Grudziądz in north-central Poland. The Franklin Aircraft Engines firm has obtained the Production Certification from the Federal Aviation Administration in the US. This certification gives the Franklin Aircraft Engines firm the capability of supervising and approving all production of both whole aircraft Franklin engines and their parts. The initial production of widely used Franklin engines marked by O-235 (4A-235) and O-350 (6A-350) is underway. Nevertheless, it is limited for now to manufacturing much-needed spare parts. Today multiple representatives are trying to bring the Franklin aircraft engines back to life. However, US owners of Franklin engines (powering Stinson and Bellanca airplanes, etc.) cannot use much of Polish parts because of their slightly-different dimensions before the period of Polish production and problems resulting from legalities.Regarding the Franklin engines themselves, they have always had a good reputation, and, especially, the six-cylinder versions are well-known for very being smooth.Chris Heintz developed a four-seat sport STOL aircraft with the following brand name: Zenith STOL CH 801 [3]. The high-lift features of the design give this aircraft its excellent short take-off and landing capability. The airplane, Zenith STOL CH 801, was designed to provide excellent STOL performance without the need for excessive aircraft engine power. The Franklin aircraft engine O-350 (6A-350) shown in Fig. 1, from the Franklin Aircraft Engines firm, is a popular alternative engine choice for the Zenith STOL CH 801 kit aircraft, providing plenty of power at an affordable cost.

Fig. 1. Franklin aircraft engine O-350 (6A-350) mounted in the Zenith STOL CH 801 airplane.

2 Factors affecting power and torque of airplane reciprocating engines

Both nature causes and issues concerning aircraft engines may adversely alter airplane performances. All aircraft engines are rated according to their ability to do work and produce power. Factors, which affect the power outputs of reciprocating engines should be discussed briefly. It should be recalled that any typical aircraft piston-engine intakes air from the ambient atmosphere, adds fuels, ignites the fuel/air charge, and extracts power from the heat and expanding gases generated by the combustion process. Anything that, unfavourably, affects the air-quality has an impact on the power output of the aircraft piston engine [4]. When the airplane engine is not equipped with some form of supercharging, which increases the pressure of the intake air, this airplane will encounter great difficulty for ascending to a service ceiling above 4,600 m. Therefore, each plane has a service ceiling, which prescribes its highest altitude capability to achieve. Another factor affecting the power outputs of reciprocating engines is temperature. A key variable involved in determining the performance of an aircraft for any given day is temperature. Flight manuals of airplanes contain some information about their performance conditional on ambient temperature, making known how much runway is needed for take-offs, climbs, and landings. Both airplane and engine performances, which depend on ambient temperature, are associated with Charles' Law describing how gases tend to expand when heated. Air humidity is also a relevant meteorological variable, which affects the efficiency of airplanes. The high humidity adversely affects the performances of both airplane wings (aerofoils) and engines. In particular, when an airplane tries to take off, the lift force created by the wing's airfoil has less capacity to support the airplane weight. There is less oxygen per unit air volume if some part of the ambient atmosphere space is occupied by the water vapor. Therefore, less oxygen is pulled in during each intake stroke. Hence, the ability of the fuel-air mixture to burn changes adversely.

In an internal combustion engine, petroleum-based aviation fuel is burned with oxygen in the air. Seventy-eight percent of the whole air volume is nitrogen, and twenty-one percent is oxygen. The heat energy generated by burning the gasoline and oxygen mixture is absorbed by nitrogen and gaseous by products' combustion. Then, their expansion turns the heat energy into mechanical power. The mixture proportion of aviation fuel and air by weight is of extreme importance to engine performance.Changes in airplane altitude affect, directly, both the pressure and temperature of its surrounding ambient air and, in consequence, on the air volume. Therefore, the airplane altitude change can cause the variation of the weight composition of a mixture of air and gasoline at a constant throttle position controlled by the pilot. It is worth recalling that when air and gasoline mixtures have the ratio of air to fuel between values from as rich as 8:1 to as lean as 16:1, they will burn in any engine cylinder. However, when mixtures have compositions by weight, which are beyond the range of these ratios' values (i.e., when these ratios are either less rich or much lean), such mixtures may cause a work stoppage of any reciprocating engine. One element that harms engine performance is poor ignition. Any defect that reduces the magnitude of the spark may result in a reduction of engine power. If the ignition timing occurs too late than the correct timing ignition, the created by the combustion process heat energy is not fully transferred to the piston work. Hence, some portion of the heat energy escapes through the exhaust system. As a result of this, the exhaust gas temperature increases. In turn, during the compression stroke, the piston may absorb more heat energy than assumed when the ignition timing occurs too early while the piston travels up. Hence, it may create detonation of the air and fuel charge and, besides, causes a loss of engine power.

A reciprocating engine running near full obtainable power requires a gasoline-rich to air mixture to prevent overheating and detonation.The cooling action of gasoline-rich mixtures results from the excess fuel over that needed for its combustion. If the air to fuel ratio is below the value of 14.9:1, the unburned fuel cools the internal cylinder surface. The high fuel consumption performed by the aircraft reciprocating engine at this moment is not such an important issue since, generally, this engine operates at full power for only short periods.When, for a long time, the engine runs near its maximum output of power efficiency, the use of very lean in gasoline mixtures may lead to a loss of its power and, farther under certain conditions, the severe its overheating. The checking of cylinder head temperature gauge is essential when the engine operates on very fuel-lean mixtures. Besides, if the mixture is excessively fuel-lean, the engine may backfire through the air injection or, eventually, might be stopped totally. Such explosion may be in place at (i) intake manifold and pipes, (ii) carburetor, or air-control section, and (iii) air scoop and ducting.If the air-fuel mixture is not fully consumed and removed from the previous cycle is still burning when the engine's intake valves open up, the fresh air-fuel mixture ignites from the old burning one. Thus, owing to the incompletely burnt mixture rest, the resulting flame travels back to the engine's induction system. Detonation and pre-ignition are peculiar combustion deteriorations, which significantly diminution the engine's power output. An unintentional detonation occurs when an uncontrolled burning of the air-fuel mixture upon ignition is in one of the engine cylinders by exceeding the safe limit values of both temperature and pressure for a given fuel.In turn, pre-ignition also occurs when something in the cylinder becomes an incandescent source of the pre-ignition of the air-fuel mixture before the occurrence of the intended usual ignition event. The ongoing influence of high temperatures above 900°C of exhaust gases at the surface of a selected engine component might create dangerous conditions. For example, an out-of-order outlet valve generates a leak through which exhaust gases flow. Such a leak will cause the outlet valve to overheat due to the lack of adequate cooling of its surface. When the valve edge is flamed by the fire, the air-fuel charge might ignite during the compression stroke, i.e., before spark plug sparking.

3 Torsional vibration damping systems

As described in the previous section, during the design of torsional vibration damping systems, factors, which affect both the power and torque of airplane reciprocating engines cannot be omitted.Torsional vibrations of combustion engine crankshafts result directly from that combustion engines create the fluctuating torques in a pulsating manner like any reciprocating machines by burning processes in internal combustion chambers. These processes generate cyclic loads applied to crankshafts. Namely, during the power stroke, gas pressure forces create four-times greater torque than an averaged torque established for a complete cycle sequence of each cylinder. In each cylinder of a four-cycle engine, the gas pressure force goes through an entire cycle every two revolutions. The resulting vibration order generated by the pressure force is the one-half number of cylinders in a multicylinder engine when all cylinders contribute equally. Besides, the spacing between combustion events is equal. However, due to compression friction, gas exchange, and other losses, even a negative torque is delivered to the crankshaft during the remaining three strokes. Such torque pulsations lead to variations of the rotational speed of the crankshaft. Hence, the resulting torque depends on the cylinders' number and, also, the firing order. Torsional vibration causes a frequency and (or) phase modulation of an otherwise uniform angular velocity of the crankshaft, which can easily be measured by laser torsional vibrometers or encoders attached to the crankshaft. The torsional response of the rigid crankshaft results from a torque action generated by each engine cylinder. Besides, this response is a good indicator of combustion uniformity. Torsional vibrations increase stresses in crankshaft webs. Load and unload oscillatory of crankshafts noses, engine camshafts, and their accessory drives cause the significant increase of propulsion systems' wear and the engine noise [5, 6]. Efficient damping of disadvantage torsional vibrations of crankshaft needs to specify both the crankshaft model and its excitations in the form of torques applied to mechanical arrangements associated with each cylinder.The crank gear of the engine can be modelled by a spring-mass system. This system is excited to vibrate by periodic tangential forces. Such forces cause oscillating rotational movement of mass lumps concentrated at the crankshaft (i.e., oscillating torsion of its segments), which overlaps the actual rotational movement of the crankshaft.

Rotational movements of the crankshaft comprise three components:

- regular rotation corresponding to the rotational speed,
- fluctuation of the rotational speed (known as static speed fluctuation) as a result of the action of a varying tangential force over a power cycle,
- vibration over the displacement angle originating from the tangential force operation (i.e., dynamic speed fluctuation).

It is worth noting that crankshafts, with both higher stiffnesses and lower inertia moments, stand out higher natural frequencies. In turn, lower natural frequencies have crankshafts with higher inertia moments by adding counterweights to them. If external periodic forces act on mechanical systems, they cause the systems to assume different vibration behaviour [7]. Namely, the systems vibrate, after a transient phase, at frequencies of exciting forces. Resonances occur when frequencies of natural vibrations correspond to frequencies of the exciting forces. Without damping, the vibration amplitude would reach an infinite value. Damping reduces vibrations without exception, whereas the damping strength always influences the vibration amplitude.

Without reference to particular solutions, basic types of recognized systems for vibration damping: [8]:

- **Slipping systems**: Energy is removed from the system. The energy removal can be hydraulically achieved, such as in a torque converter or through engaged friction, like in a clutch mechanism,
- **Passive systems**: Energy is stored, temporarily, and can be alternated between its kinetic and potential forms, such as, in a classic spring-mass damper, a dual-mass flywheel (DMF), or a centrifugal pendulum absorber (CPA), which temporarily store potential energy in the centrifugal-force field,
- **Active systems**: Energy is supplied to and extracted from the system, externally. To produce a counter-excitation, which actively damps vibrations, an electric motor

in the powertrain can be, for instance, applied. Another possibility is an application of semi-active systems, in which a parameter, such as a spring rate, is accordingly tuned.

Quite often, satisfying results can also be accomplished with an efficient combination of all of these systems, predominately.

The first practical use of the dynamic torsional absorbers had been implemented for airplane engines by the World War II outbreak. In this respect, a torsional vibration absorber developed for an aero-engine manufactured by Havilland Engine Company [9] is a representative example. This absorber was used for the overcharged six-cylinders version of the mass production engine Havilland "Gipsy" designed by Frank Halford.

Modern internal combustion engines (ICE) reach higher peak pressure thanks to the improved thermodynamic processes and charging technologies. Passive vibration damping approaches encounter essential demands, which encourage the implementation of semi-active or active methods. Active reduction of torsional vibrations achieves reduced torsional oscillations using the compensation torque generated by an electric traction machine (ETM). The ETMs, which arouse particular interest, are represented by integrated starter/alternator/damper (ISAD) systems in the 5–20 kW range. The applied mechatronics technology of these systems is nearly identical to more powerful parallel hybrid systems, to which belong drivetrains of the 48 V-based mild hybrids.Such a solution opens new challenges for active vibration reduction with non-inline integration of the ETM using belt drive systems. Conducted analysis showed that the efficiency of active vibration reduction of such belt drive systems during combination with a belt-driven starter generator (BSG) depends on the control functionality [10].

It turned out that, in the case of aircraft structures, the development of only properly-working dampers of torsional vibrations is not enough for the correct operation of crankshaft-propeller systems in changing conditions during the flight. As shown in [11], discrepancies between torque-stand and flight measurements of torsional vibrations carried out on the same engine might explain propeller fractures due to bending vibrations. The work of Lürenbaum also showed the fatigue crankshafts' fractures, which were different from those created by torsional vibrations fractures, had to be attributed to longitudinal vibrations.

4 Application of torsional dampers for the crankshaft vibrations reduction

Torsional vibrations of the crankshaft negatively affect the operation of the engine. Due to the torsional vibrations of the crankshaft, opening and closing times for the valves might change. In this case, the timing gear becomes very noisy. Therefore, on six- and eight-cylinder in-line engines, the camshaft drive gears are located near the flywheel, where the rotation angle is the smallest. Crankshaft torsional vibrations cannot be eliminated. However, employing so-called vibration dampers, dynamic oscillations of such type can be, quite effectively, counteracted.

Due to quite a significant flywheel weight, it is not used for aircraft internal combustion engines readily. Let us take a look at how the flywheel works. During the power stroke of the engine, the flywheel stores the kinetic energy. In turn, during the intake, compression, and exhaust strokes, the flywheel releases kinetic energy. Therefore, in the torque vs. time course shown in Fig. 2, the spikes are dampened during the power stroke and distributed through the whole engine cycle. The higher the number of cylinders in an engine, the smoother the output torque (or power).

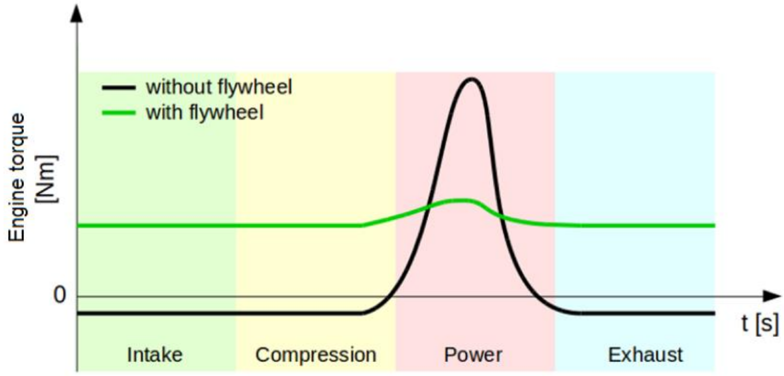

Fig. 2.Torque of the internal combustion engine during a 4-stroke cycle.

Besides, the crankshaft should be sufficiently rigid, and the frequency of natural vibrations should significantly exceed the frequency of forcing impulses (see Fig. 3, 4, 5 and 6).

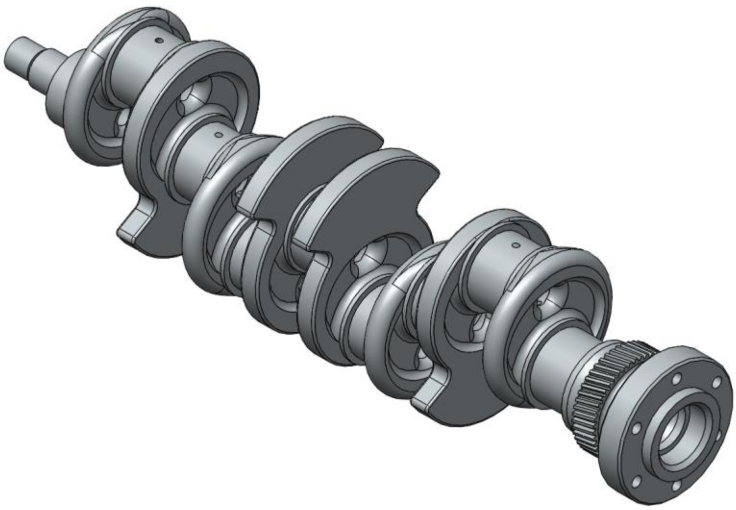

Fig. 3.Four-cycle engine crankshaft drawing made with an engineering graphics program (Increasing the number of main bearings in an engine reduces bending stress and deflection caused by the distance from the crank-pins to the nearest main bearings).

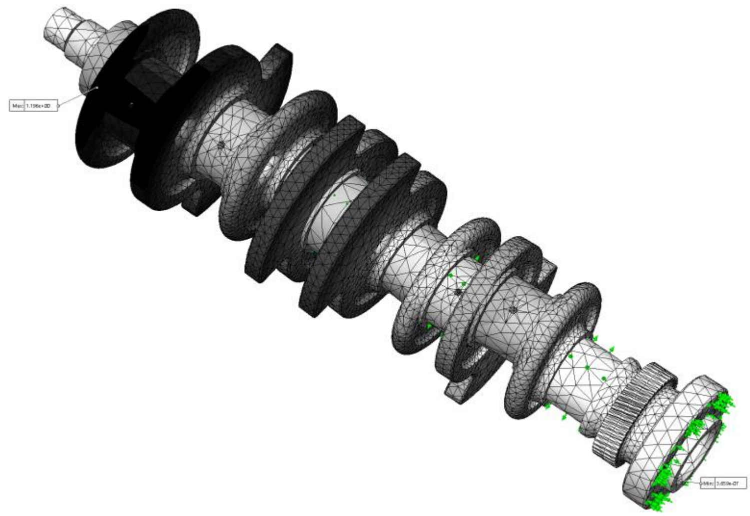

Fig. 4. First calculated natural frequency of the engine crankshaft (762.89 Hz, crankshaft fixed from the flywheel side/force transfer side).

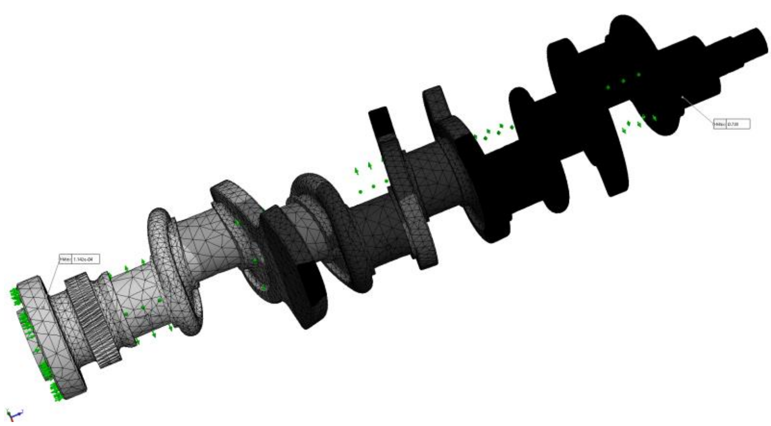

Fig. 5. Second calculated natural frequency of the engine crankshaft (1116.7 Hz, crankshaft fixed from the flywheel side/force transfer side).

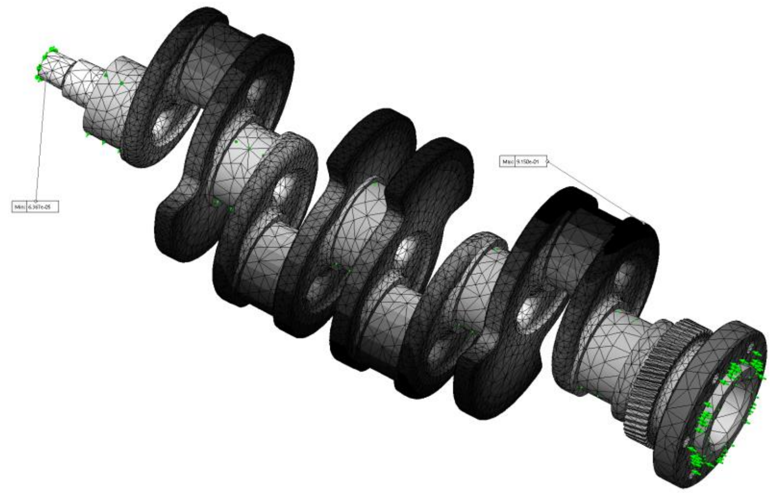

Fig. 6. First calculated natural frequency of the engine crankshaft (274.04 Hz, crankshaft fixed from the control side or drive end).

Boxer engines have low vibrations since they are the only well-known configuration, which has no unbalanced forces regardless of the number of cylinders. The weight balancing of the reciprocating parts of the boxer engines is not needed. Therefore, these engines do not require a balance shaft or counterweights on the crankshaft. In the case of boxer engines with fewer than six cylinders, rocking couples are present. Because of the distance between the crankpins along with the crankshaft, each cylinder is slightly offset from its opposing pair. However, gas pressure forces cannot be balanced. Therefore, it is legitimate to use the active vibration damping method. In a traditional four-cylinder boxer engine, the firing order is 1-3-2-4. An attempt is made with cylinders 1 and 4 firing simultaneously and then alternating with cylinders 2 and 3 like in more commonly known the "Twingle" engine (i.e., with twin firing as a single), for compensating the gas pressure forces.

5 Conclusions

The use of torsional vibration dampers facilitates the montage of any piston engine in most light airplanes. Failure to use these vibration dampers may result in the fact that even correctly designed aircraft structures will not meet the required functional assumptions.
Due to the ever-stricter emissions legislation, reducing pollutant emissions fuel consumption will play a key role in developing internal combustion aircraft engines.
Optimizing the charge cycle in combination with torsional vibrations damping is a promising approach. Reduction of both fuel consumption and emission can be expected.
Since aircraft reciprocated engines are not operated under steady-state conditions, the ability to damping torsional vibrations has to be adapted to changing operating conditions (for instance, the engine charge cycle).
Therefore, an important task is to implement flexible and adaptative control systems [6, 12] to assist airplane piston engines as soon as possible. Note that most light airplanes with reciprocated engines still have manual mixture controls. Pilots, which are duly qualified to operate such airplanes, use an exhaust gas temperature gauge (EGT gauge) to set the optimal fuel-air mixture for their power and current density altitude just like it was before.

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