A Review of the Theory of Dynamic Soaring

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Presented at the 7th OSTIV Congress, Osieczna, Poland, June 1958

In the early Twenties, when Soaring Flight was beginning to fascinate an appreciable sector of the aeronautical world, much speculation was entertained about the various meteorological phenomena which might be exploited to accomplish motorless flight. Slope soaring was the first to be understood and practiced. Next came fronts, cloud streets, then thermals. Wave soaring was not discovered until almost 20 years later. On the other hand there is a whole complex of maneuvers, designated as "Dynamic Soaring", which was recognized as theoretically possible by some of the earliest pioneers, as early as 60 years ago (viz. S. P. Langley), and which is manifestly part of the repertoire of many species of birds, although it has never yet been convincingly emulated by man in sailplanes. The question would therefore appear well in order, whether it might not behoove us to take another look at Dynamic Soaring, now that our knowledge of the mechanics of flight as well as of the movements in the atmosphere have been much advanced since, in 1923, I wrote what I then thought was a reasonably comprehensive treatise on the "Theory of Soaring Flight". It was published in 1926 in German in Volume 5 of the "Abhandlungen aus dem Aerodynamischen Institut der Hochschule Aachen" under Professor T. von Kármán, and reprinted in English abstract translation as a serial in nine issues, between those of March/April 1943 and of November/December 1945, of the magazine "Soaring" of the Soaring Society of America.

If we take such a new look now, we should do this largely for reasons of academic curiosity and perhaps in an endeavor to demonstrate the validity of the theories by experiment wherever this can safely be done, but not in pursuit of any exaggerated hope or dream of opening entirely new sources or avenues of aerial transportation. It is fairly safe to say that any exploitation of dynamic soaring effects will exact compromises in regard to comfort of pilot and passenger and to the expeditious execution of any preplanned flight mission, with the exception of the special case of the climb in a gradient, which is indeed a good and useful trick. Most of the dynamic soaring maneuvers which we observe birds to execute are not very attractive for manned sailplanes to be even tried. For one thing we cannot venture as close as the birds to dangerous obstacles at which certain dynamic effects originate; secondly, some of the meteorological perturbations to which these birds can react are simply too small for the much larger and less maneuverable manned sailplanes to navigate.

Dynamic Soaring has been defined as the art of extracting energy in flight from variations of the wind, in contrast to what might be termed Static Soaring, namely the gliding in air that has a steady rising component. Variations of the wind may be temporal or local. The temporal varations are in the nature of gusts or turbulence which travel with respect to the ground, either with the velocity of the average wind or with some other velocity of propagation; they can be encountered by an aircraft in random fashion or in a sequence utterly difficult to predict even where there are systematic anisotropic features present in them. The local variations are bound to some prominent features of the topography or geography of the terrain; they can be systematically encountered by deliberate maneuvers with reference to the terrain. Whether this differentiation can always be established is perhaps open to conjecture, but it is a helpful concept for purposes of analysis. Where the situation is clear, a plan of action for experimental exploration can be mapped out.

Perhaps the simplest case amenable to demonstration and in fact already demonstrated in some little known experiments some 40 years ago is the exploitation of the friction shear or wind gradient over plains, as it occurs under many common conditions in many localities. It was demonstrated by Wolfmüller with his coupled kites, one flying in a high layer, the other in a low layer of stable evening air. Tied together, they could be set to sail away at an angle to the wind, without a string held from the ground. A more practical application is the trick of climbing a (powered) aircraft against a wind which is steadily increasing with altitude. As the aircraft climbs it enters layers of increasing headwind which acts dynamically just as though an inertia force equal to the product of the vertical wind gradient by the rate of climb were pulling the craft forward. This effect improves the climb performance in proportion. Conversely, if one were to climb while headed down wind, the effect would reduce the climb performance. In a gliding descent the situation is reversed; unfortunately it has caused many an accident when the aircraft attempting a slow but steep approach against a stiff headwind would stall when reaching the lower altitude where the wind was weaker due to ground friction. Comparative measurement with calibrated aircraft under wind conditions which are simultaneously surveyed by sounding balloons or, better, recording anemometers mounted on towers, would throw an interesting light on this. A sailplane might theoretically stay in self-sustained climbing flight once it is towed into a condition of climb such that its rate of climb $dh/dt = g\varepsilon/(dw/dh - g/v)$ where w is the wind velocity at height h, ε is the glide ratio of the aircraft and v the velocity. This condition can however be fulfilled only where the wind gradient is so fierce that it is greater than g/v; say over 50 ft./sec per 100 ft. altitude. I doubt that such a situation might occur even below a jetstream and extend through a layer of several 100 ft. Encountering it would undoubtedly be a hair-raising experience. A difficulty would still be to prove that there was no vertical component of the wind present at the same time and place. Vertical components would readily be

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[1] Douglas Aircraft Co., Inc., Santa Monica; Soaring Society of America.

created if a wave is generated as it well might. In fact, unusual conditions of thermal stability would have to prevail to prevent wave formation in the boundary region adjoining a high wind aloft of jetstream proportion. Deliberate experiments to demonstrate exploitation of vertical gradients are difficult to execute, because extreme conditions may not last long enough or remain constant to permit running a flight test and also organizing a satisfactory meteorological survey of the wind profile, making sure to what extent vertical currents complicate the situation.

On the other hand, the exploitation of a vertical gradient of the (horizontal) wind need not be confined to a single climb. It can be repeated after a deliberate descent, but the descent should be preceded by a 180° turn so as to be headed in the opposite direction, i. e., downwind. This furnishes another gain, which is captured in the form of surplus flight speed, welcome to execute another 180° turn to face upwind again for another climb cycle. Maneuvers of this kind might be spectacular and interesting in an academic sort of way, but far be it from me to recommend them as a means for sustained flight especially in view of inevitable hazards of executing maneuvers close to ground where appreciable vertical wind gradients are most likely to be encountered.

Wind gradients also occur in the horizontal plane, between wind streams of different velocities. Such differences can be generated by localized meteorological effects, notably in mountainous regions and, as we now know, in the vicinity of the jetstream. If in such a border region there prevails a steady gradient (Γ), that is a gradual transition from one wind speed to another, over a certain distance, one can readily envisage a systematic exploitation of this energy source by crossing it at a bias course (Θ) at constant apparent air speed (v) in which case the gain in terms of apparent reduction of the glide ratio ε is $\Delta\varepsilon = -(\Gamma v/g) \cdot (\sin 2\,\Theta/2)$. It is greatest, viz.$-\Gamma v/2g$, for a course of $\Theta = 45°$. If the width of the gradient zone is not extensive, then one can try to exploit the situation by means of circling flight maneuvers repeated by crossing the border region, always heading upward against the stronger wind and downwind with the lesser wind. Again any attempt to demonstrate this kind of operation scientifically would require simultaneous wind observations covering several points in the area and the duration of the flight maneuvers, hence, a considerable amount of preparation and apparatus plus advance knowledge of the occurrence of the phenomenon, certainly an ambitious project. The problem is further aggravated if the phenomenon is masked by turbulence. This is likely to be the case because while vertical layers of air can be stabilized by the existence of a low or inverted temperature lapse rate, no similar stabilizing influences are likely to favor a laminar character of the boundary between two flumes of different wind speed in juxtaposition.

Turbulence can be generated and fed by many causes, and it has a wide spectrum of amplitude, frequency and direction. Much has been learned about it in extensive research carried out by observation both from the ground and in instrumented flight. To be sure, the phenomena appear quite different from different observation points. A free balloon drifts with the wind, only in the vertical can it have a different velocity than the ambient air mass, namely when it is lighter or heavier. In the horizontal it senses only accelerations. From a ground stationed mast an anemometer and weather vane measures the relative wind velocity and direction with respect to the ground. Variations of them can be interpreted as fluctuations of the wind as it sweeps by this station. In an airplane however, the frequency and sequence of the encounter of variations of the wind vector depend on the aircraft's own motion through the air. Hence, in order to infer atmospheric turbulence from measurement on board an aircraft, one must record not only the accelerations but also the maneuvers of the aircraft relative to the air mass, and then one must correlate these records with the progress of the aircraft over the terrain or through the meteorological structure to be studied.

We speak of gusts and lulls when we observe surges or abatements of the wind with time from a fixed station. In flight people sometimes loosely speak of a gust whenever they observe a variation from the steady state equilibrium of lift against weight (and centrifugal force in a turn) and drag against thrust and zero side force, without really knowing whether the meteorological situation into which they flew was stationary with respect to the ground, i. e., a boundary between layers of different winds or a real gust in the sense of a temporary surge. We may wonder in what way this makes any difference. It does insofar as where stationary, terrain-bound or front-bound shear zones exist, we may learn how they are organized and plan a series of flight maneuvers to exploit them. Not so with the gustiness of random turbulence; to exploit it we would have to learn to predict the gusts and to do that we would have to recognize some regularity or order in their occurrence. A vast amount of observational material has been ammassed. However, as far as I am aware, no system of correlating their frequency, amplitude, and polarization with measurable parameters has yet been demonstrated, with the exception of those conditions perhaps, where the orographic origin of the disturbance governs the phenomenon as for instance in mountain waves, and in those conditions where regularly patterned clouds make the structure of a standing or traveling wave complex visible.

If, or where, we could predict the gusts which we are to encounter, a number of methods should lend themselves to their exploitation, as has been explained theoretically by various authors: the easiest to understand is the trick of waiting for a head-on gust, then either with the excess air speed so gained or after converting it to altitude gain, make a 180° turn and await the lull which is bound to come, but is sensed as another head-on gust in the opposite heading. Repeat to suit! Less drastic variants of the same idea are: to fly a course across the predominant gustiness direction (if such a predominance exists!) and either deviate in snake-like movements, always towards the relative gusts, or subtler yet, merely bank alternately to the right and left, always cleverly showing the raised wing to the swell. Another somewhat complicated technique has been computed to wrest energy from horizontal gusts by performing roller-coaster like climb and dive maneuvers which however must not only be tuned in proper synchronism with the gusts, but also rendered asymmetric by superimposing a first harmonic over the fundamental mode of elevator pumping action. This technique would seem rather hopeless to learn without some foreknowledge of the existence of some systematically periodic gust structure. At best the effect would be small. Therefore, there is little incentive for attempts to demonstrate this type of dynamic maneuver in flight.

This is even more appreciated when it is considered that in many real situations gustiness does not predominate in one horizontal direction (e. g., that of the average wind) but it will have three components in space, two horizontal, one vertical. The mechanism of the exploitation is fundamentally different for the horizontal than for the vertical. One can say: of the turbulence in three dimensional space it is the horizontal component of the variation of acceleration and the vertical component of the variation of velocity which must be caught to wrest energy from the wind in flight.

Thus it will be understood that the utilization of vertical pulsations in the atmosphere requires a different type of soaring maneuver which is indeed easier to execute. The general rule is: make more lift when the air goes up, and less when it goes down. As a matter of fact, no deliberate maneuver at all may be necessary to get some benefit from vertical wind components fluctuations, because if the aircraft possesses any longitudinal inertia at all and is aerodynamically of indifferent longitudinal stability, the resultant angle of attack will vary in the right way. More yet can be gained if the pilot pulls up when he senses uplift, and pushes forward slightly when he senses down stroke. Contrary, the gain is reduced or nullified when he or the effect of high longitudinal stability tends to keep the angle of attack constant. This illustrates the general fact that any attempt to smooth out or alleviate the gusts, thus catering to the comfort of the passengers and reducing the stress peaks on the aircraft works contrary to the utilization of dynamic soaring and, vice versa, any useful dynamic maneuver will be hard on passenger and aircraft. It should also be noted that there may be conditions where some systematic correlation between the vertical and horizontal gustiness components exists, for instance near the ground. Here the wind shear tends to pair down-gusts with increased wind speed, up-gusts with decreased, thus mitigating the disturbing effect for aircraft flying upwind, and rendering it more treacherous for the one flying downwind, close to the ground.

A few words should perhaps be said about flying through vortex fields. It is relatively easy to picture what dynamic reactions should be suffered by an aircraft flying essentially horizontally through a vortex formation having its axis horizontal across the flight path like in the case of the penetration through the rotor or roll cloud structure often found in lee of a mountain range below a standing wave: the result would be essentially that of flying through first a strong up-current, then a strong down-current (or vice versa), this sharpness of the border being governed by the amount of vorticity present. Horizontal vorticity may also be encountered in free air, for instance between layers of different wind velocities. Whether its exploitation by dynamic soaring effects or maneuvers might be feasible is perhaps debatable; to prove its accomplishment would again be a difficult task.

Vortices with vertical (or slant) axis are common in the atmosphere. They come in all sizes ranging as they do from cyclones and anticyclones extending over hundreds of kilometers to the tiny dust devils most frequently seen in desert country. The former are too large, the latter too small, to be dynamically exploitable. Between them, however, are those of dimensions of hundreds of meters, commensurable to the diameter of circling flight maneuvers. Often their core is made up of rising air and the bird circling in the core region would be soaring statically. What, however, happens when he is circling around the core in air that is not rising but merely in circular motion? There would have to be a radial pressure gradient. It stands to reason that flying in the sense opposite to the vortex rotation should be better than flying around overtaking it, mainly because the bank angle, and hence, the drag penalty due to the centripetal component of the lift is less. Just what, if any, dynamic benefit could possibly be derived from such a situation is not obvious. In the last analysis any energy gain by the dynamically maneuvering bird or aircraft can only come from the force field which created the vortex and kept it going. In my earlier studies of the 1920's, I considered another type of cylindrical air motion with vertical axis in which a sizable air mass was visualized as under the rhythmic influence of exterior harmonic pressure pulsations of slow frequency, circularly polarized as it were, when the East-West component has a 90° phase shift against the North-South component. In such a condition an aircraft could conceivably so circle with the same rotational period, that it would always experience a useful acceleration vector and, so to speak, support itself by centrifuge action. Whether such situations actually occur in the real atmosphere, and under what conditions, might be the subject of discussion and possibly clarified by a review of existing observational data. Extensive dynamic meteorological measurements which will be gathered by the well instrumented meteorological research airplanes in operation now and in the future, are bound to throw more light on this. Sounding rockets fired upwards into the atmosphere have been made to leave smoke trails which make gradients in wind velocity visible so that they can be evaluated from time lapse pictures.

The question may be asked whether there may be some wind conditions we have not thought of yet. While it is obviously impossible to predict what may still be discovered in the future one may look at the problem in a morphological manner; it then appears that one can consider 9 components of the wind gradient, viz. the rate of change of the 3 velocity components (forward, sideways, and vertical) in each of these 3 directions, and 3 acceleration components, and we have looked at all twelve of these.

The summary which I formulated in the concluding installment of the series published in the November/December 1945 issue of the magazine «Soaring» is probably still essentially correct, viz.:

"Dynamic soaring maneuvers have been deliberately tried by expert pilots but the results accomplished are insignificant and uncertain. Our 'feel' is admittedly undeveloped and it is difficult to learn to decide when a positive lift surge is caused by a vertical or a head-on gust, which should be distinguished and differently parried... Instruments for detecting atmospheric energy which utilize optical, acoustical, radio and thermic gust and thermal gradiometers for detecting this energy have been proposed and tried. Even if the sailplane could be equipped with the most elaborate instrumentation, completely describing the aerodynamic and dynamic flight parameters, the information conveyed by it would not enable the pilot to determine and execute the maneuver which would wrest the maximum of energy from whatever gustiness he encounters. While the problem of automatic stabilization of aircraft in essentially straight or steadily turning flight has been solved to a reasonable degree of accuracy the same is by no means true for soaring flight involving dynamic maneuvers. In fact this constitutes a much more formidable problem. In order to determine the status of acceleration of a surrounding mass of air it is necessary for a complete solution of dynamic soaring automatization to resort to instruments responsive to terrestrial 'fields' independent of those detected by air speed meters, wind vanes, yawmeters, altimeters, gyroscopes, accelerometers, and the like. Magnetic, optical and radio devices have been considered, but no scientifically complete system has yet been demonstrated." (Perhaps this statement deserves revision?) "As to the application of soaring flight techniques, both static and dynamic, to powered aircraft, it has been established that under favorable circumstances performances can be improved and hazards overcome by clever tactics and it is in this respect that experience gained in soaring flight will stand a power aircraft pilot in good stead."

However, now with over a dozen more years of history, development, and knowledge accumulated, it may well be worthwhile for the new generation of sailplane pilots to report any further experience they may gain with dynamic situations, observations, and experiences, and those who are in a position to carry on meteorological observations of ever increasing scope with ever more elaborate instruments both from ground stations and from aircraft will undoubtedly have the gratification of finding their researches rewarded bey their contribution to the further enhancement of flight safety and man's mastery of the air.