Operational benefits of a regional airliner due to fly-by-wire

Ing. Petr Liškář

Supervisor: Prof. Ing. Alexander Beinusov, DrSc.

Abstract
Článek popisuje některé nové možnosti využití systému fly-by-wire u dopravních letounů na krátké tratě. Nejprve jsou stručně rozebrány dominantní vlivy působící na vlastnosti a výkony letounu v průběhu jeho vzletové fáze a uveden fyzikální princip možností výkonnostních vylepšení. Následně jsou představeny nové funkce řídicího systému. V závěru je stručně popsán dynamický model vytvořený v programu Matlab a uvedeny další, dosud nevyčerpané možnosti, které systém fly-by-wire pro řízení letounu nabízí.

Keywords
Fly-by-wire, operational benefit, regional, airliner, turbopropeller, turboprop, take-off, performance, airplane, aircraft, flaps, aileron droop

1. Introduction

In general, fly-by-wire (FBW) is an aircraft control system replacing the mechanical interconection between the control stick and the control surfaces of the conventional manual flight control system with some electronic interface. The pilot's commands are translated into an electronic signal and pilot's force is replaced with the power of the actuators driving the control surface deflection.

As the signal is run through the embedded system the response of the controlled surfaces does not has to be proportionally equal to the pilot's input and can be modified in desired manner. For example this is typically used to help to increase the aircraft stability, to reduce the wing and the tail stress load, or to control the aeroelastic effects. Also, the weight benefits when comparing to the manual system are usually within the scope of interest. But surprisingly, there still is much more that should be controlled.

2. Market situation

2.1. Business jets, commercial and military aircraft

For a long time the FBW systems were only installed either on the military aircraft, large commercial airliners or business jets. The high purchase price of the system did not allows to do otherwise. For military aircraft or business jets the investment to the FBW system is easily balanced by the maneuvrability benefits in the first case and flight comfort in the second, while the large commercial airliners profit from considerable benefits in terms of lower Direct Operating Costs (DOC) through reduced maintenance requirements, greater flexibility and reduction in weight caused by elimination of fewer mechanical moving parts. Furthermore, long distances and quantity of passangers help the operators to speed up the return of investment.

2.2. Regional airliners

For the smaller aircraft or aircraft with lower capacity the situation is not so obvious. Significant changes on processes (especially certification, manufacturing and maintenance) and required investment on the manufacturer side had exceeded the potential product improvement for a long time.

However, due to factors such as increasing fuel prices and environmental issues, the situation has changed in last few years and even the conservative producers of the smaller regional airliners as the turbopropeller aircrafts incline to use this system.

The principal advantage in the form of lower DOC remains similar to the larger aircraft. But unlike the commercial airliner on its transcontinental flight, the flight path of a regional airliner is very specific, as shown on the figure Fig. 1. Note, that a transcontinental flight consists from the cruise phase almost from 80%, whereas for a regional airliner is very rare the cruise phase to pass over 20% of the total flight time! Therefore even more operational benefits due to the FBW control system installation should be introduced in this category to prove the concept.

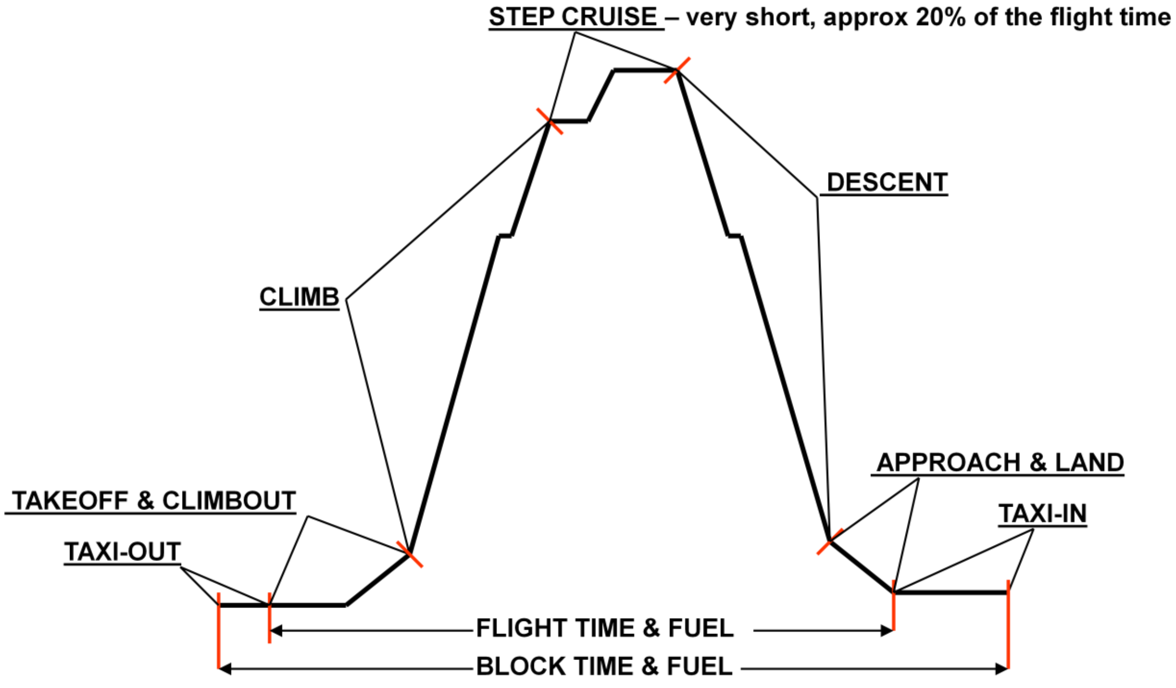

Fig. 1 *– Flight profile of the regional airliner [1]*

3. Performance analysis

3.1. Introduction

Regional aircraft are dedicated to operate mainly from the local airports. These might be located in defavorable locations and can suffer from related limitations such as high altitude, obstacles laying in their close proximity and significantly shorter runways when comparing to the huge international airports. These facts put the high pressure notably on the aircraft take-off and landing characteristics and may cause some of the airports to be restricted. Any significant improvement on this field would be well apreciated from the safety reasons and operational point of view as well. The number of potential destinations might grows up as some of the airports become attainable.

This paper focus notably on the take-off performance improvement.

3.2. Basic assumptions

For the purpose of the analysis it is assumed that any possible weight saving which may be achieved by FBW implementation will be used by the manufacturer (OEM) to increase the payload or extend the range taking extra fuel. In reality that means, the maximu take-off weight remains the same. For this reason the focus is on area of control laws of the control system and how they can possibly help to reduce the take-off length.

4. Take-off performance analysis

4.1. Preliminary analysis

In general, the most important factor of the each take-off is its length. Let's assume the take-off length is mainly driven by parameters associated with the aircraft as such. The take-off weight was neglected, but for example take-off speed and acceleration and other parameters, such as environment and atmospheric conditions remained. Taking care of the first two seems to be a good approach when looking for the improvement, if there is any. Both take-off speed and acceleration could be driven by the airplane behavior itself and therefore, however the impacts of the FBW control system on the take-off performance are not obvious yet, we should look closer to them.

Acceleration during the take-off is a function of the mass of the aircraft, engine power and aerodynamic qualities in the take-off configuration. Take-off speed is referred to the lift force generated by the airplane surfaces. Based on the empiric experience it is assumed the most important part of the take-off procedure is take-off run. The preliminary take-off configuration is on the table Tab. 1.

Tab. 1 *– Preliminary aircraft take-off configuration*

c_l [-]	S [m^2]	MTOW [kg]	v_r [$km.h^{-1}$]	acc [$m.s^{-2}$]
1.9	73.9	32700	220	2.1

Where c_l is a lift coefficient, S is wing surface, ***MTOW*** means maximum take-off weight, v_r express rotation speed and finally ***acc*** is a 0.74 time the maximum acceleration that could be achieved during the take-off. The value is considered as an average acceleration during the take-off for the propeller driven aircrafts in preliminary analysis [8].

Given values leads to the refference take-off run distance:

Let's suppose following single improvements in increasing lift coefficient by 6% and acceleration by 4% would be achieved. As show the tables Tab. 2 and Tab. 3 the take-off run distance is then reduced by almost 50 metres.

Tab. 2 – Impact of the particular lift coefficient improvement

Improvement of	c_l + 6% [-]					
	2.014					
Leads to the result	Δv_r			ΔL_{run}		Total L_{run}
	[%]	[km.h^{-1}]		[%]	[m]	[m]
	-2.87	-3.4		-5.66	-50.3	837.8

Tab. 3 – Impact of the particular acceleration improvement

Improvement of	acc + 4% [m.s^{-2}]					
	2.184					
Leads to the result	Δv_r			ΔL_{run}		Total L_{run}
	No impact			[%]	[m]	[m]
				-3.85	-34.2	**853.9**

These simplified results shows how relatively minor changes in acceleration or lift coefficient improves the take-off run performance. But these improvements could be coupled together and combined.

Suppose following combined improvements (Tab. 4) would be achieved:

Tab. 4 – Impact of the combined lift coefficient and acceleration improvement

Improvement of	c_l + 6% [-] & acc + 4% [m.s^{-2}]					
	2.014 & 2.184					
Leads to the result	Δv_r			ΔL_{run}		Total L_{run}
	[%]	[km.h^{-1}]		[%]	[m]	[m]
	-2.87	-6.4		-9.29	-82.5	**805.6**

These combined results seem to be very promising and deserve more attention. The take-off run is reduced by more than 10%. Remaining question how could FBW control system act to achieve presented expectations is the topic of the following chapters.

4.2. Take-off procedure

Regular take-off procedure request wing flaps to be deployed to take-off position when the aircraft is standing still at the beginning of the runway. Hence, they are deployed from the very beginning phase of acceleration until the airplane reach certain altitude. This allows the airplane to get into the air at lower speed and to reduce the risk of stall shortly after the lift-off.

Unfortunately, based on wing and flap design, an airplane with deployed flaps generates more drag and pitching moment during runway acceleration than the airplane with clean wing configuration. This penalty may be partially balanced by additional lift production at the same time, but experience with some aircrafts shows the negative effect can be much more significant. Therefore, an airplane with deployed flaps has worse acceleration, than it would have in the clean wing configuration and longer take-off run as a result. If initial drag and pitching moment of flaps is eliminated, better acceleration is obtained and the lift-off speed may be achieved in shorter distance and time. This all leads to take-off length reduction, which brings an important advantage to many airliners which operate at obstacles' avoiding conditions, high altitude elevation airports and others. Thus, this feature adds interesting market advantage to the aircraft manufaturer which supports these airliners.

4.3. Procedure improvement

General idea and probably the only possibility of FBW contribution to the pure power performance is to improve airplane's lift-to-drag ratio and alleviate pitching moment influence by driving the flaps during the take-off itself. Flaps position may be driven from zero or clean wing position to take-off setting during acceleration phase in order to reduce the dominant drag contribution. The crucial control element would be namely the airspeed.

Once the FBW control system is installed it is not an issue make the ailerons to be deflected symmetrically and use them as a high lift device in addition to the actively controlled flaps. Such a procedure called aileron droop is very suitable to be implemented during the final phase of acceleration because this considered configuration increase the aircraft's lift performance by lowering lift-off speed and reduce take-off distance.

4.4. Physical approach

The flap and ailerons position can be controlled in such way that transition from the "clean wing" drag polar curve to the flaps take-off drag polar curve (see illustrative figure Fig. 2) is optimized in sense of drag and pitching moment minimization during acceleration phase. The control law can be then designed by taking into account some easily measurable parameter as airspeed and for sure considering some disturbing factors, such as deployment speed for example. This approach is not necessarily the only for optimal transition but it still guarantees noticeable reduction in the take-off distance with respect to the current approach in aircraft design processes.

4.5. Safety risks

To provide required safety level, the flaps position must always reach take-off setting before the decision speed v_1 is reached. This control will be performed automatically by on-board computer. The usage of the system will then not present any extra workload for the pilots comparing to the recent situation.

If for any reason flaps cannot reach take-off position before the decission speed v_1 is achieved, several solution is proposed:

- the warning message which informs pilot about insufficient flaps position is displayed
- based on the airplane characteristics (weight, engine power, wind speed), minimum recommended deployment angle might be calculated
- in case of unsatisfactory system or airplane performance automatic take-off abort procedure might be executed

In any case, the system shorten the take-off run distance and in every critical situation adds more decision time, which is positive as well.

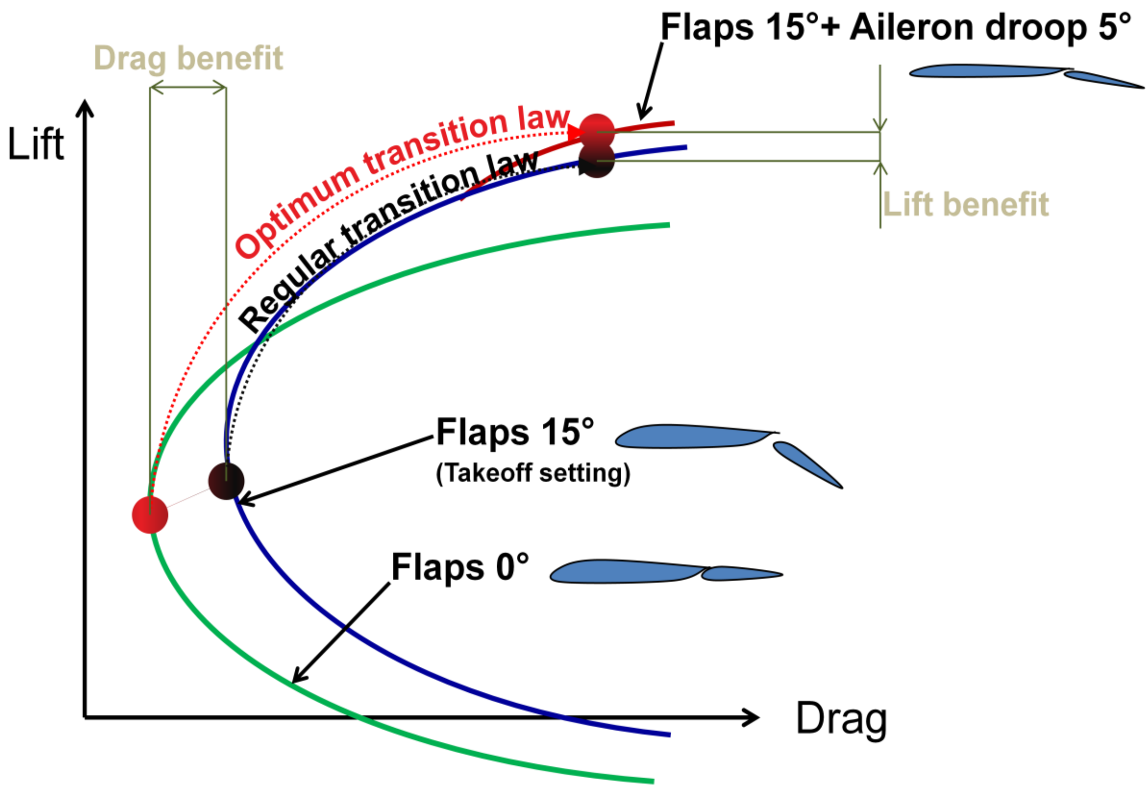

Fig. 2 - Drag polar curve for considered wing configurations

5. Verification

5.1. Introduction

To verify postulated ideas it was decided to apply it on the numerical generic airplane model. Model of a regional turboprop was built up based on basic available data sheets, where missing dataset was derived from ATR-72 aircraft. This approximate model was considered for validation of proposed control law and for preliminary assessment on other benefits in term of take-off length.

Verification of control law for this category is very important as supposed this airplane will operate very often from various regional airports where short take-off length can be, beside the others, a significant restrictive factor for airline operators.

Next, it is assumed that the considered airplane will be equipped with FBW control system which allow implementation of such control law. But the example provided below can be implemented for any future model equipped with FBW flight control system, where wing/flap/aileron design meet basic assumption that the airplane with deployed flaps generates more parasite (drag and pitching moment) than positive effect (lift performance).

5.2. Take-off definition

For the purposes of the control law evaluation, take-off itself was divided into three phases.

The first phase is acceleration from 0 kts to v_1, the second phase is acceleration from v_1 to v_r and the third phase is a time from the beginning of rotation to the lift-off (reaction force on main landing gear = 0 N). The take-off length for the validation purposes was defined as a distance from the point where speed is 0 kts to the point where lift-off speed is achieved – see figure Fig. 3. This is the principal phase of our interest.

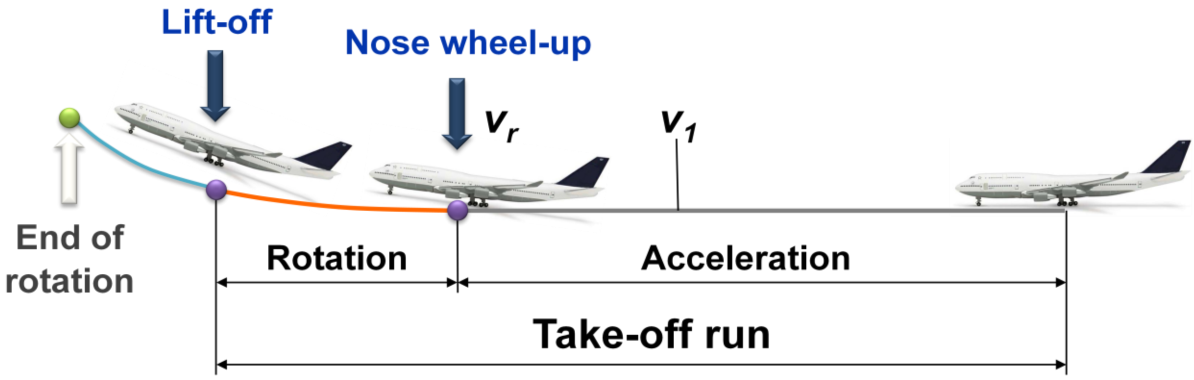

Fig. 3 *- Takeoff phases and take-off length definition*

5.3. Model description

It is necessary to calculate course of acceleration of the airplane and time required for achieving the rotation speed. Then angular acceleration in rotation phase needs to be found. Angle of attack changes during the rotation affect significantly lift and drag and we expect an important reduction in acceleration. The process is teminated when reaction force on main landing gear drop to 0 N which simply indicates the lift-off. The airplane becomes the airborne since then.

Different cases and configurations need to be processed and compared. To solve this problem, aerodynamic model of the turbopropeller airplane was built up using the *.m-file script in the Matlab® environment and used for the following dynamic calculation model.

The dynamic calculation model is based on the Newton's second law and is expressed as the ordinary differential eqation of second ordre. Double-integration of the process results in the missing take-off run lenght. Simple Euler numerical method is used for the solution. That means, that resistance forces and thrust forces are compared in the loop to get the acceleration at any given time.

Following forces and moments acting on the airplane were taken account in the model (see figure Fig. 4):

- Lift and drag forces generated by wing, flaps, ailerons, rudder and horizontal tail (i.e. horizontal stabilizer and elevator), landing gear and fuselage
- Aerodynamic moments generated by wing, flaps, ailerons, and horizontal tail
- Engine and propellers thrust curve as a function of the airspeed
- Moments generated by thrust forces
- Main landing gear and nose wheel reaction forces and non-linear rolling resistance forces
- ISA atmosphere model, surface roughness, runway slope and elevation effect

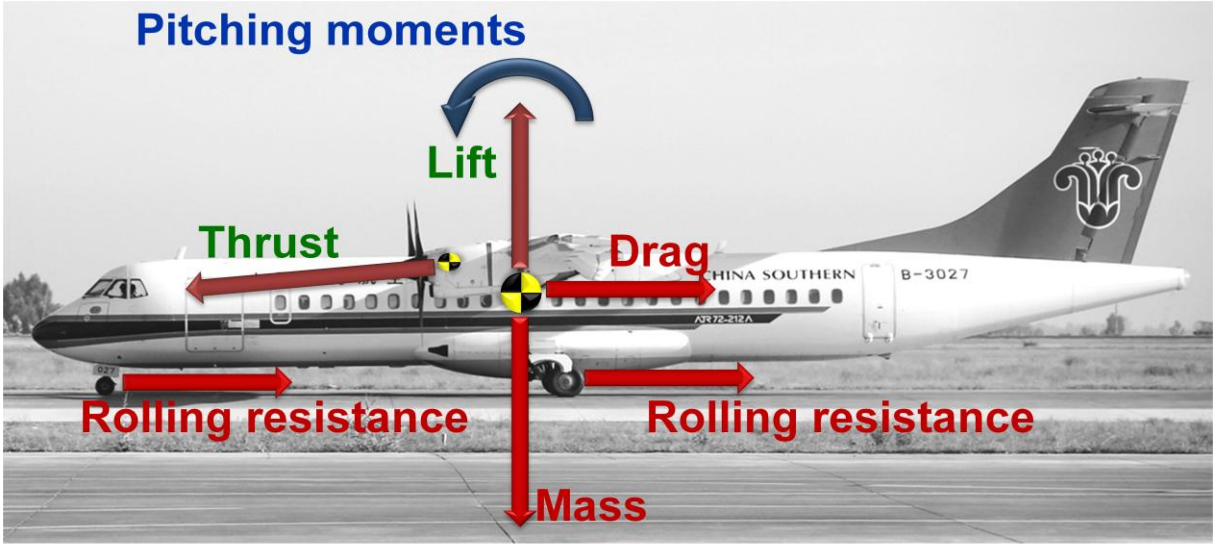

Fig. 4 *– Schematic representation of considered forces and moments [2]*

The airplane aerodynamic model is loaded by certain error and model may not fit exactly, but the most important thing is the very same model is used for evaluation and comparison of the dynamics of all different take-off scenarios regardless if new FBW system features were virtually installed or not. Because of that, the same error was introduced to each considered scenario, therefore results obtained should be used for comparative analysis. Degree of confidence in results for specific aircraft varies with given airplane data quality and complexity.

5.4. Evaluated Scenarios

Four scenarios were considered and evaluated to validate proposed control law.

Scenario 1 - considered airplane with default flap position 15 deg as a take-off position, horizontal stabilizer at 0 deg, elevator deflected to -20 deg from the beginning till lift-off and no aileron droop is applied. This scenario defines default take-off configuration and set up the baseline.

Scenario 2 - was the scenario where flaps were set to default position 15 deg at the beginning and constant aileron droop 5 deg was applied. The horizontal stabilizer and elevator settings were the same as for the first scenario.

Scenario 3 - use flaps position driven by airspeed and aileron droop driven by airspeed. Flaps start to deploy from 0 deg to 15 deg at the speed 35 kts with rate 1.4 deg/sec. Aileron droop started at the speed 60 m/sec with rate 5 deg/sec, 5 deg offset of ailerons was used as a target aileron droop position. The horizontal stabilizer and elevator were set in same way as in previous scenarios.

Scenario 4 - uses flap position driven by airspeed as implemented for scenario 3 and no aileron droop (aileron offset equal to 0 deg whole the time). Elevator and horizontal stabilizer were set in the same way as in previous scenarios.

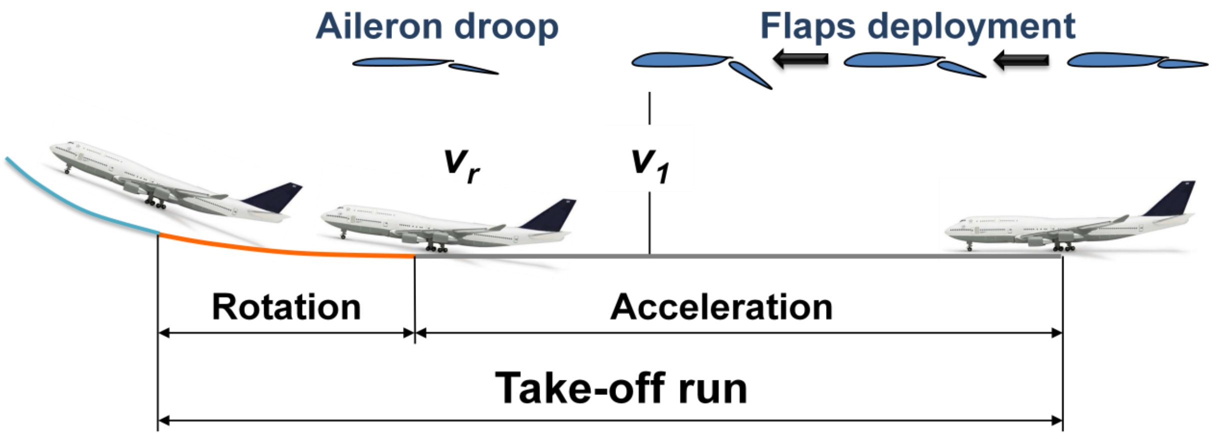

***Fig. 5** - Flaps position based on airspeed*

6. Results

All four scenarios were implemented and take-off lengths were compared. The results are summarized in the table Tab. 5 below.

***Tab. 5** - Take off length for considered scenarios – normal operation*

Scenario	Flap position	Aileron droop	Lift-off speed	Takeoff length
Scenario 1	15 deg	0 deg	130 kts	1583 m
Scenario 2	15 deg	5 deg	124 kts	1453 m
Scenario 3	0 deg -> 15 deg	0 deg -> 5 deg	124 kts	1316 m
Scenario 4	0 deg -> 15 deg	0 deg	130 kts	1491 m

The first scenario simply sets our baseline. It is a typicall value for regular ground run for this type of airplane.

Scenario 2, simple aileron droop, which means the default aileron offset from the beginning, with default take-off flap position will reduce the takeoff length per 130 m while proposed combination of continuous flaps deployment combined with aileron droop in Scenario 3 will reduce take-off length per **267** m – thus proposed control laws may reduce takeoff length per **16.8%** in comparison with baseline scenario.

The fourth scenario shows that for the airplane with considered aerodynamic parameters where just flaps are driven by a control law does improve takeoff length for less than 6% and for this reason and for given airplane it seems reasonable to consider combination of both control laws only. This result may vary aircraft to aircraft based on wing/flap/aileron and tail design. Of course should be even further optimized.

Following figures Fig. 6, Fig. 7, Fig. 8 illustrate behavior of the airplane aerodynamic model and show the results of the dynamic analysis for all 4 considered scenarios. The most promising is the red line of the Scenario 3.

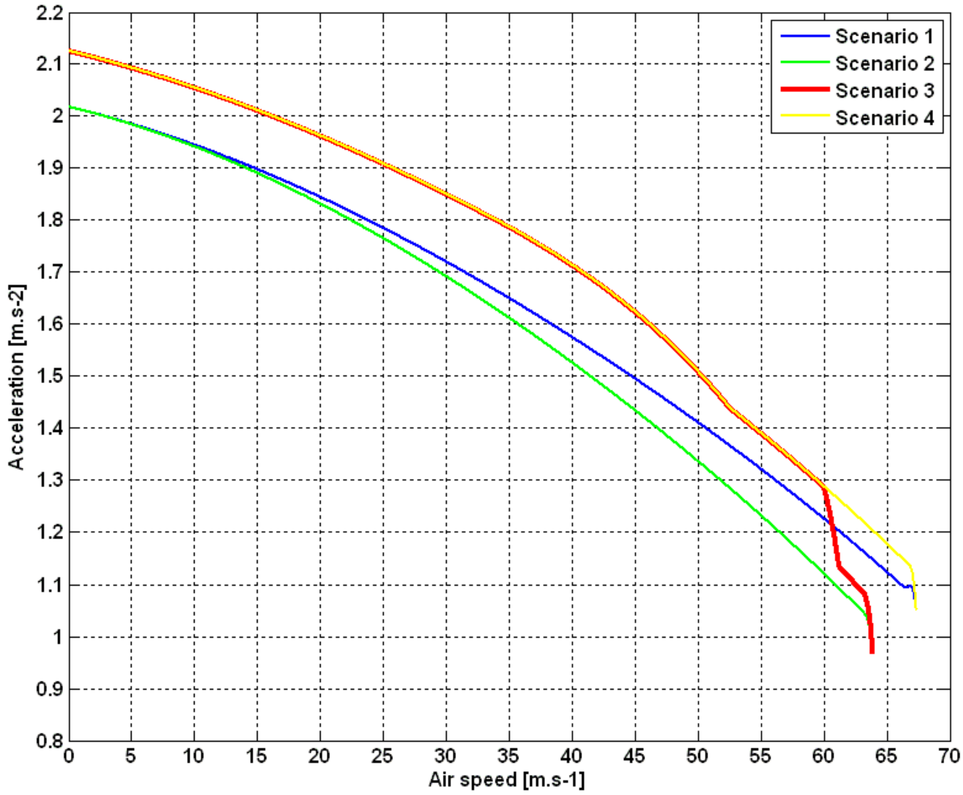

Fig. 6 - *Acceleration per time for the four scenarios*

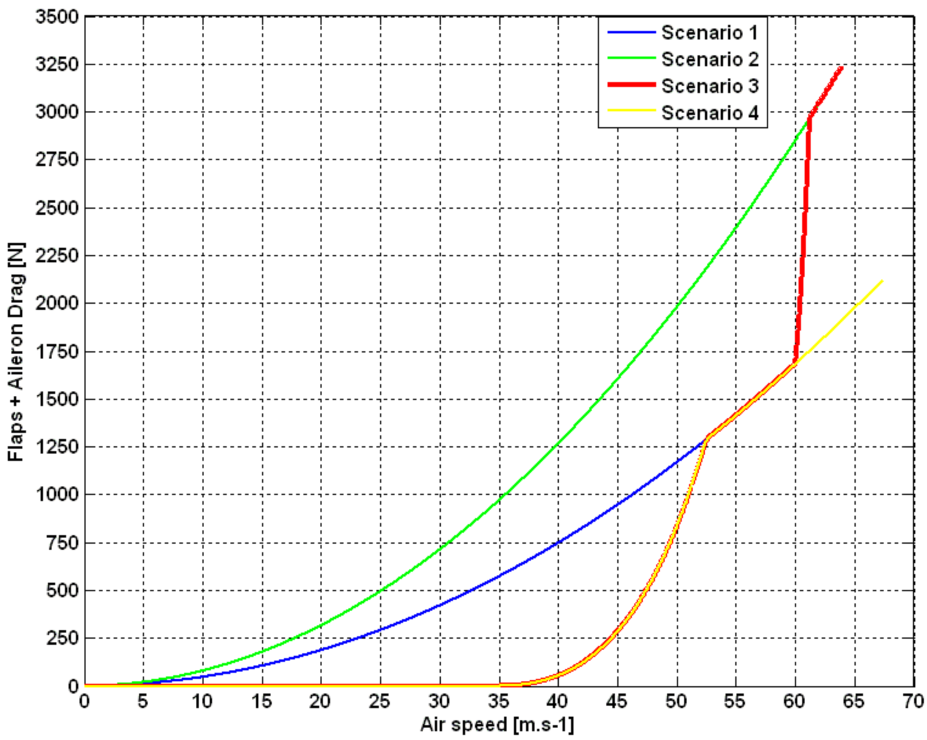

Fig. 7 - *Flaps and ailerons drag force component*

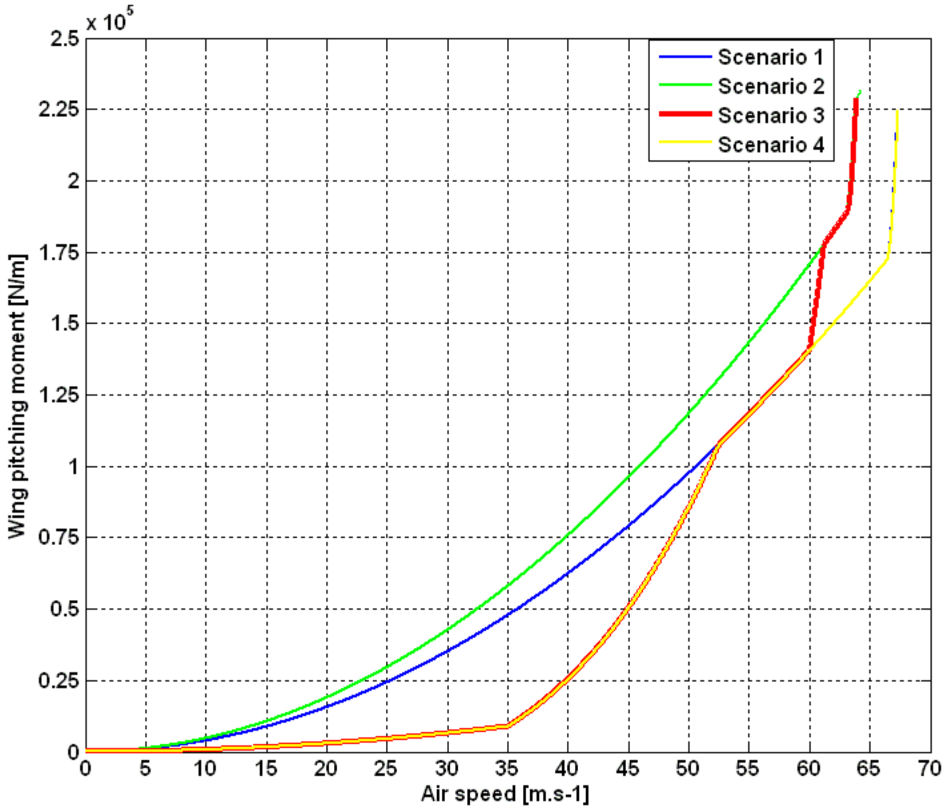

Fig. 8 *- Wing pitching moment*

7. Conclusion

New possible functionalities of the FBW control system for small commercial aircraft were introduced. The integrity of the proposed system was evaluated using aerodynamic model of the regional turbopropeller airliner. Physical background of the new features was presented, while the benefits and advantages of this solutions were calculated and verified by dynamic model in Matlab® environment where shortening of the take-off run by almost 17% was achieved. Elementary control law based on the the airplane airspeed were proposed for flaps and ailerons operation control. The proposed solution does not expect any drastical changes in airplane design and present a subject to further development.

List of symbols

acc	Acceleration	[$m.s^{-2}$]
c_L	Lift coefficient	[-]
L_{run}	Take-off run	[m]
MTOW	Maximum take-off weight	[kg]
S	Wing area	[m^2]
v_1	Critical engine failure recognition speed	[kts]
v_2	Takeoff safety speed	[kts]
v_r	Rotation speed	[kts]
$v_{lift\text{-}off}$	Lift-off speed	[kts]

List of abbreviations

DOC	Direct Operating Costs
FBW	Fly-by-wire
OEM	Original Equipment Manufacturer

References

[1] More turboprops coming to the market – maybe, CAPA website last accessed 11/16/2011 http://www.centreforaviation.com/analysis/more-turboprops-coming-to-the-market---maybe-30634

[2] Airliners website last accessed 2/16/2012, http://www.airliners.net/aircraft-data/stats.main?id=257

[3] Internal documentation, ATR CM DO/TM-6595/10, 14/12/2010

[4] Internal documenation, ATR CM DO/TY-3228/10, 17/06/2010

[5] Torenbeek, E.: Synthesis of Subsonic Airplane Design, Delft University, 1998

[6] Roskam, J.: Airplane Design, part 6, Ottawa-Kansas, 1990

[7] Babikian, R.: The Historical Fuel Efficiency Characteristics of Regional Aircraft from Technological, Operational, and Cost Perspectives Dept. of Aeronautics and Astronautics, Massachusetts Institute of Technology, 2010

[8] Jean-Luc Boiffier : Dynamique du Vol de l’avion, Supaéro, Toulouse 2001