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CIVIL APPLICATIONS OF THRUST VECTORING - AN EXPLORATION

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Abstract

Following recent military thrust vectoring developments, it was considered worthwhile to study *civil* applications of thrust vectoring. The study provides a comprehensive overview of the subject in a qualitative and exploratory fashion. It identifies three main areas of importance: aircraft economy, aircraft safety, and thrust vectoring system layout. It is postulated that a certain economic benefit is a prerequisite for introduction of thrust vectoring into civil aviation.

The following results were found. *Economic benefits* are hard to be solidified due to a variety of drawbacks and limitations. The best prospect is offered by thrust vectored flight control (TVFC) of semi-tailless airliners. *Safety benefits* are likely to be achieved, mainly in the field of TVFC complementing conventional flight control systems. However, the introduction of an additional primary aircraft system presents a strong adverse safety aspect. The most versatile *system layout* is that of vectored exhaust nozzles. The required thrust vectoring system technology can be converted from current military systems.

Overall, it was established that, although several benefits are possible, the various adverse factors dominate the problem area at present. A net benefit may result for future aircraft by integrating thrust vectoring technology into the design process from the outset.

Introduction

The benefits of military thrust vectoring have clearly been demonstrated.(1) Military thrust vectoring results in, among others, increased agility and improved STOL (Short Take-Off or Landing) characteristics. Following extensive R&D, military thrust vectoring is technologically mature.(2)

This knowledge leads to the question whether benefits can also be realised in civil aviation. The presented study, carried out at Delft University of Technology, was performed in order to identify and analyse potential benefits conceptually.(3)

The so created overview can suggestedly be used as a starting point for further research, since the subject is basically new. Previous work is limited to studies of Prof. Gal-Or at Technion - The Israel Institute of Technology.(4) In his proposals the emphasis is placed on thrust vectoring flight control (TVFC). In contrast to these studies, in the here presented study a more broad exploration was pursued, to provide a more comprehensive overview of the subject.

The scope is restricted by taking into consideration only civil subsonic jet transports. Obviously, civil aviation is characterised by different priorities when compared to military aviation. Aircraft economy and safety, rather than agility, are of main interest.

Economy was considered to be of such importance, that it was adopted as postulate that a solid benefit in aircraft operating economy is a prerequisite for introduction of thrust vectoring into civil aviation.

Economic benefits

This section gives an overview of suggested thrust vectoring economic benefits, which were divided into three areas:

- STOL applications
- TVFC applications
- Cruise configuration optimisation

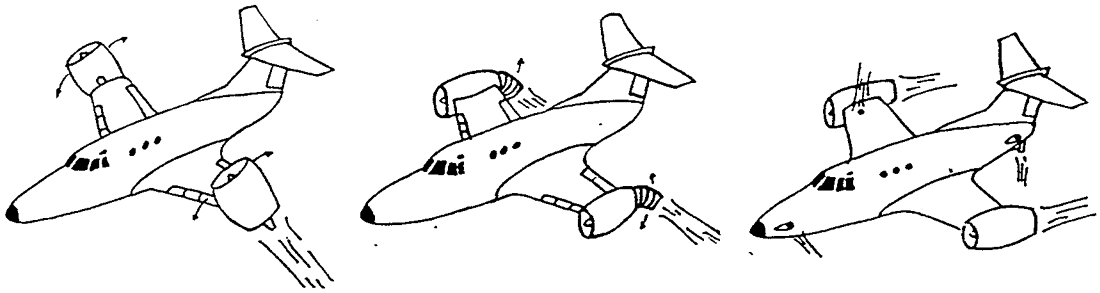

Figure 1. Thrust vectoring principles: tilt-engine (left), tilt-jet (bottom right) and reaction control (top right).

STOL applications

STOL applications are associated only with pitch thrust vectoring. Three concepts are discussed:

1. Direct lift in approach and climb
2. Early take-off rotation
3. Vectored-thrust blown flaps

For direct lift applications, downward vectored thrust can be interpreted as a direct contribution to aircraft lift. The amount of additional lift is however hampered by the relatively low thrust/weight ratios of conventional civil transports. Also, in order to fully utilise the available thrust for lift augmentation, large vector angles are required, which make the vectoring systems complex.

Early take-off rotation is based on successful military results of thrust-induced pitch-up during the take-off roll.[5] This application requires tail-mounted engines, opposed to the wing-mounted engine of the above direct-lift application. However, current FAR operation regulations (V_{MC}, V_R, V_{MU}) basically prevent earlier rotation of civil aircraft.

Vectored-blown flaps are suitable for the known non-vectored-blown flap methods and overcome the requirement of the latter for large flaps with given large-diameter fans. For a given blown-flap system, this could result in reduced weight and complexity of the flap system. Nonetheless, blown flaps are only rarely applied in civil aviation and carry a large number of drawbacks.

In short, STOL applications yield little realistic perspective.

TVFC applications

Thrust vectoring flight control denotes the method of using vectored thrust to control an aircraft, thereby replacing or complementing the conventional aerodynamic flight control (AFC) system. The benefit lies in a weight and drag reduction of removed or downsized tail sections. Also, a clear safety benefit exists (see safety section). A main consideration for TVFC is the aircraft configuration with respect to engine location: Tail-mounted engines provide yaw and pitch control, wing mounted engines provide roll control. A mixed configuration (e.g. two engines wing-mounted, one in tail) is the most versatile.

TVFC applications are split into two groups:
TVFC *replacing* AFC, i.e. tailless aircraft and TVFC *complementing* AFC, i.e. semi-tailless aircraft or aircraft with downsized tail sections. The first option is barely feasible for conventional aircraft configurations since the horizontal tailplane is required for a force equilibrium that cannot be realised by vectored thrust without dramatic increases in fuel burn and required engine thrust. The most realistic option is the latter one, where yaw thrust vectoring may replace the vertical tail section or allows a reduced-area fin.
For a B727-100 with removed fin section and installed yaw thrust vectoring system, a cruise drag reduction of approximately 6% and weight reduction of 1% MTOW were calculated. This translated to some 6% fuel burn reduction for a given flight profile. This led to a DOC-reduction (Direct Operating Cost) of between 1 and 2%.

This figure resulted from a simple modification, without re-optimising the design. It is expected that, with a fully integrated thrust vectoring system into a new design, a weight multiplier effect and re-optimised cruise flight condition may increase this figure to maximum 4%. On the other hand, this result ignores

Table 1. Performance applications overview, comparative

– –	Very negative	++	Positive
–	Negative	**	Required
0	Doubtful or marginal	*	Useful
+	Reasonable		

Application	**Suitability of Engine configuration**			**Impact for best configuration**		**System requirements**			
	Rear	*Wing*	*Both*	*Benefit*	*Drawbacks*	*High-rate*	*Multi-axis*	*Differential*	*Large angle*
STOL	–	++	+	0	–				**
TVFC tailless	+	0	++	–	– –	**	*	**	
TVFC semi-tailless	+	0	+	+	–	**	*	**	
Cruise optimisation	+	+	+	0	–				

adverse effects of increased maintenance, initial and R&D costs. These costs are largely unknown, but were expected to nullify the reduced costs.

Cruise configuration optimisation

The last suggested option for economic benefit is to reduce fuel consumption by optimising the cruise flight thrust vector. An optimal thrust direction would be slightly nozzle-down with respect to the flight path direction and relieves lift and hence drag of the wing. It has been shown that the benefit is marginal.(6) Another option is cancellation of the frequently installed sideways engine inclination that reduces the one-engine-out (OEO) thrust asymmetry. Yet other options are further optimised engine nacelle-wing interaction, as well as improved inlet flow conditions. Effectively, thrust vectoring uncouples the engine thrust vector and nacelle vector directions. Again, all profits are marginal and are expected not to outweigh thrust vectoring installation penalties.

Summary of economic benefits

An overview is presented in table 1 of the various suggested applications for aircraft economy. The given results are for comparative purposes only. Qualitative comparisons are presented based on the associated aircraft configurations, the strength of benefits and seriousness of drawbacks for the best configuration, and the required advanced thrust vectoring system capabilities. An explanation of these system requirements is given in the systems section.

It is obvious that the various applications require different aircraft/engine configurations and that they have different needs for the thrust vectoring system capabilities. This limits the number of possible simultaneous applications into a single aircraft.

Further, all benefits were considered marginal at best, for present conventional aircraft configurations. It is expected that a positive net result requires integration of thrust vectoring into the design process of future aircraft from the outset. Possibly, adjusted configurations may prove more suited to thrust vectoring applications.

Overall, the necessary economic benefit as postulated is hard to solidify. The best perspective is offered by semi-tailless TVFC applications, specifically aircraft with a removed or downsized vertical tail section. Stability and control can presumably be taken over by an aft-mounted thrust vectoring installation. The use of thrust vectoring for flight control was evaluated by computer simulations and will be covered in the simulations section.

Safety

The purpose of the safety analysis is identical to that of the preceding economic section: To identify potential benefits in the field of safety.

Five potential applications are studied:

- TVFC with asymmetric engine failure
- TVFC with aerodynamic flight control failure
- TVFC action following stall

Table 2. Safety applications overview, comparative

– –	Very negative
–	Negative
0	Doubtful or marginal
+	Reasonable
++	Positive
**	Required
*	Useful

Application	Engine location			Impact for best configuration		System requirements			
	Rear	*Wing*	*Both*	*Benefit*	*Drawbacks*	*High-rate*	*Multi-axis*	*Differential*	*Large angle*
Engine failure	++	0	+	+	–		*	**	*
AFC failure	++	0	+	++	– –	**	**	*	*
Stall recovery	+	–	+	+	–	*	*	*	*
External hazards	+	0	+	+	–	**	*	*	*
Direct Lift Control	–	++	+	+	–	**			

- External hazards
- Direct-lift control

In addition, adverse safety proved essential and will be discussed below as well.

Engine Failure

Yaw thrust vectoring may restore aircraft moment and force equilibrium after asymmetric engine failure. The effectiveness depends on the engine location and maximum attainable thrust vector angle. Rear-mounted engines provide the best perspective. The system provides additional control margin and relieves the crew from continuous rudder corrections or is useful on semi-tailless aircraft (see the economic section).

AFC Failure

A more broad application is again thrust vectoring flight control, to replace or complement aerodynamic flight control (AFC) after failure. Conventional port/starboard differential engine thrust may provide some directional control but introduces difficulties as well.(7) The potential of TVFC depends more than any other application studied on the following factors:

- Engine locations (wing, aft, both)
- Thrust vectoring system capabilities (pitch, yaw)
- Nature of AFC failure (loss of element, blockage in any position)

Combinations of these factors were studied to find that best effectiveness is reached by rear-mounted engines for yaw control. Blockage in an extreme position of both elevator and variable tailplane is practically insurmountable by thrust vectoring.

For most applications, however, a high-rate computer-controlled thrust vectoring deflection system is required. Just as with the economic perspectives, the various applications require different aircraft/engine configurations, thus limiting the number of simultaneous benefits.

Stall recovery

Low-altitude stalls still occur, often resulting in accidents. An immediate observation is the relatively poor performance of aerodynamic flight control in the low-speed region where stalls most naturally occur. The superiority of thrust vectoring systems is obvious, since there is no direct influence of airspeed. Thrust vectoring is not beneficial with powerful aircraft control to enable quick *recovery* from the stall condition. This would minimise the altitude loss during the stall and provide additional control against roll-yaw coupling at high-alpha conditions.

The thrust vectoring system must primarily be equipped with pitch vectoring, but yaw and roll control are also favourable. Rear-mounted engines are required.

External hazards

Among others, meteorological circumstances may produce hazardous flight situations, which can lead to situations of stall or failure as were described above.
Icing may lead to stall, both symmetric and asymmetric and hence thrust vectoring is beneficial in this case (see above).
Wind shear presents a stall danger as well, usually at low altitude.
Cross wind is not really a hazard but a normal operating condition. It becomes dangerous in cases of extremely

strong wind or in combination with other hazards. Then, thrust vectoring may improve aircraft control. Also, a reduced fin size resulting from thrust vectoring is helpful.
Bird strikes may cause both engine and AFC failure. Thrust vectoring potential depends on the detailed character of the damage.

Direct-lift control

A final option studied was direct-lift control on approach. The background to this principle is that the conventional longitudinal controls of pitch for glide slope corrections and thrust for speed corrections are not uncoupled. Accidents have taken place to which this problem has contributed.

The used term is an 'unstabilised approach'. The power of direct-lift control lies in the possibility to generate the required small vertical accelerations by pitch-vectored thrust. The required amount of thrust and the vector angle are small, so that the limitations of direct lift for STOL do not apply.

The main drawback is the demand for a high-rate computer-controlled vector system. Also, only wing-mounted engine configurations are applicable.

Adverse safety

A key issue in the entire safety analysis is the adverse safety that comes with an additional aircraft system. A thrust vectoring installation has two major drawbacks.

Firstly, the operability of the system is directly related to that of the engine of which it vectors thrust. Since engine failure is considered to be still the most frequent serious failure, the thrust vectoring system(s) of the remaining operative engine(s) must be capable of compensating for the lost control contribution of the failing engine.

Secondly, depending on the requirements of the thrust vectoring system (see section systems), the installation can become very complex. Hence, a large number of failure modes, interactions, reliability analyses and improvements etc. are required prior to introduction into civil aviation. The difficulty is that there are no systems to refer to or to compare with. The demands placed on military systems are different, and so are the engine layout and operation. Hence, certification must be performed from the basis, which effectively prohibits introduction of thrust vectoring into civil aviation at the current economic climate in aviation.

Summary of safety applications

Table 2 summarises the results of the safety-related issues.

As with the economic applications above, it is seen that the applicability of thrust vectoring for safety purposes is strongly configuration dependent. Rear-mounted engines are generally most suitable and wing-mounted engines are hardly of any interest for safety applications of thrust vectoring.
Also, most applications need one or more advanced system capabilities, thereby paradoxically hampering certification as discussed above. Finally, adverse system safety is found to be dominant in the case for thrust vectoring.

Thrust vectoring systems

So far, no details of thrust vectoring systems were considered. In order to maintain the broad scope of the study, three different implementations of thrust vectoring will be compared (see figure 1) in order to come to a final choice of a system suited for civil applications:

1. Tilt-engine
2. Tilt-jet
3. Reaction control system (RCS)

The three methods were compared on six criteria, namely:

- Multi-axis vectoring capability, which denotes the capability of *simultaneously* vectoring of a single system in both the lateral and vertical (yaw and pitch) directions.
- Range of thrust-deflection angles, varying from some 20° for the simplest systems, to 100°.
- Part of total thrust that can be vectored, mainly determined by choosing between vectoring fan thrust, core thrust, or both.
- Reaction speed of vectoring (deflection rate), mainly prescribed by thrust vectoring system inertia and actuation method.
- Thrust vectoring system complexity and reliability, which strongly depends on the specific system layout and performance.
- Thrust vectoring system installed weight

An overview of the results is given in table 3. Prime conclusions are the following. Tilt-engines involve high penalties with respect to weight and complexity. Reaction control systems produce only very low vectorable thrust levels (compared with e.g. RCS system in the Harrier fighter aircraft). Tilt-jet systems are effectively known as vectoring nozzles and appear most versatile.

Fourteen proven and proposed military vectoring nozzles were identified in the open literature and studied in more detail.

Table 3. Basic thrust vectoring concepts

– –	Very negative
–	Negative
+	Reasonable
++	Positive

Concept **Characteristic**	**Tilt-engine**	**Tilt-jet**	**RCS**
Multi-axis	–	+	++
TV angle range	++	+	++
Thrust Level	++	+	– –
Reaction time	–	+	++
Complexity	– –	+	+
Weight penalty	– –	+	+

They are categorised according to three criteria:

1. Axisymmetric *versus* 2-D nozzles
2. Single-axis *versus* multi-axis capability
3. Geometrical location of vectoring actuation: Upstream of the nozzle, at the nozzle, or downstream of the nozzle.

Table 4 shows most of these 14 systems and their categorical subdivision. The names denote specific systems, methods, or classes of systems.

A synthesis towards a final system was made taking into account known essential differences between military and civil engines. Among others, typical civil characteristics are:

- Bypass ratio and core/fan flow mixing
- Nozzle pressure ratios (NPR)
- Presence of afterburner and -duct
- Presence of variable throat exhaust nozzle
- Presence of thrust reverser

These characteristics are of substantial importance. For example, separated core/fan exhausts require dual vectoring systems for both flows. Also, modern high bypass ratios are relatively difficult to install at the aft fuselage location, which was found to be most favourable. Further, the absence of an afterburner duct reduces the number of suitable thrust vectoring systems, since some of them require a certain duct length from the exhaust nozzle forward.

For multi-axis vectoring purposes, which is required for many applications, the proven General Electric AVEN (Axisymmetric vectoring exhaust nozzle) is selected (see figure 2). This nozzle has been used in the MATV F-16 projectwith a GE F110 engine and performed well.(8, 9) It features a relatively small deflection angle of 20° in all directions, but is capable of deflection rates of over 60°/s.

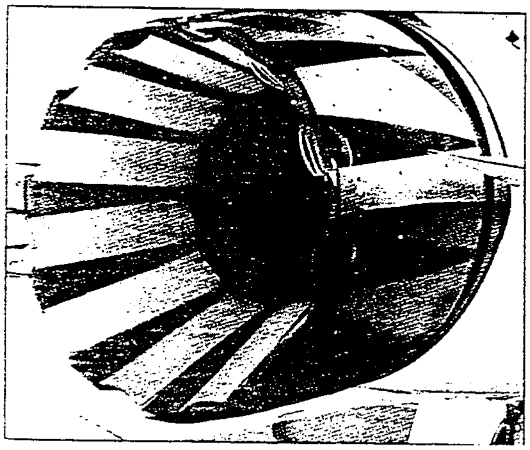

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Figure 2. The General Electric Axisymmetric Vectoring Exhaust Nozzle[8].

The AVEN nozzle leaves the original nozzle contour untouched and its layout is relatively simple compared to the original GE F110 engine nozzle.

Certainly, it is more complex than present civil nozzles, particularly since thrust reversal must be incorporated as well.

Table 4. Subdivision of several existing and proposed military thrust vectoring nozzles.
Abbreviations:

2-D C-D	*2-Dimensional convergent-divergent*
AVEN	*Axisymmetric vectoring exhaust nozzle*
CRD	*Counter rotating ducts*
PE	*Post-exit*
SCF	*Spherical convergent flap*
SERN	*Single expansion ramp nozzle*
SF	*Side flaps*

	Axisymmetric		**Asymmetric**	
	Single-axis	*Multi-axis*	*Single-axis*	*Multi-axis*
Upstream	Gimbal/Swivel CRD	SCF	Skewed throat	Double skewed throat
At nozzle		AVEN SCF	SERN Fluidic 2-D C-D	SERN-SF Cruciform 2-D C-D
Downstream	P/E-vanes	P/E-vanes	Wedge	

The transfer is, in a technical sense, feasible. The main concern is to achieve high reliability in order to counter the adverse safety issue.

For multi-axis vectoring purposes, which is required for many applications, the proven General Electric AVEN

Simulations

Following the qualitative analysis, it was considered desirable to obtain more insight in the behaviour of thrust vectoring flight control installed in large airliners. Of main concern were the available deflection rate of the thrust vectoring system and the relation between available vectorable thrust and aircraft inertia.

A number of demonstrative simulations were performed for a modified Boeing 727-100, with vertical the tail section removed. Hence, yaw thrust vectoring is required to ensure stability and control.
The simulated aircraft features a suitable configuration of three aft-mounted engines (see figure 4). It also has an engine layout that is similar to that of the GE F110 engine to which the AVEN nozzle was fitted in the MATV F-16 programme.

All simulations were performed with six-degrees-of-freedom and were non-linear with constant stability derivatives for low-altitude low-speed manoeuvres. The results were compared to similar manoeuvres with a simulated 'conventional' or 'baseline' B727-100 with aerodynamic flight controls.

Stability derivatives were available for the unmodified B727-100; the modifications were calculated using empirical methods for the influence of the vertical tail. The correctness of the baseline model was verified by comparing the five eigenmotions with the theoretically expected behaviour and was found to be credible.

Control laws were designed elementary to mimic human control rather than fully-optimised flight computer control.

The simulated manoeuvres were:

- Straight and level flight with atmospheric gust disturbance
- Yaw-vectoring standard level turn
- Asymmetric engine failure
- Slipped cross wind approach
- Crabbed cross wind approach
- Multi-axis thrust vectoring level turn

The tailless version is inherently unstable directionally. With applied artificial stability control, its motions remain much more erratic than the baseline version. It must be handled much gentler, and hence shows slower motions and larger deviations from the intended flight path.

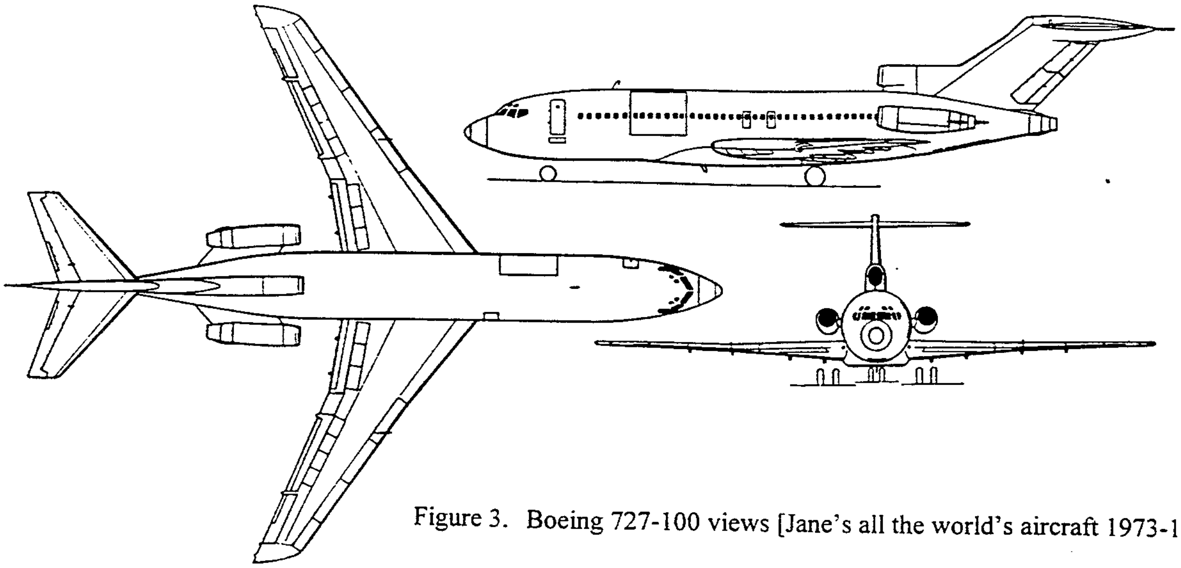


Figure 3. Boeing 727-100 views [Jane's all the world's aircraft 1973-1974].

For this aircraft, thrust vectoring proved to be badly comparable to rudder control, with opposite deflections occurring frequently. An example is shown in figure 4, which gives the simulation history for a 180° level turning flight for both versions (baseline and tailless) of the modelled B727. Presented are rudder deflection *dr* and yaw thrust vectoring deflection *dy*, roll rate *p* and roll angle μ, and yaw rate *r* and slip angle β. Generally, the turn is executed well by the tailless thrust-vectored aircraft.

Next to turn entry at t = 10s and turn exit at t = 70s, a lateral gust disturbance is visible at t = 40 s.

The occurring opposite deflections for yaw vector control and rudder control imply the need for fly-by-wire control. It also, however, hampers human control after computer control failure.

Overall, it was still concluded that thrust vector control seems feasible with the aid of computer control. The extent of the success depends strongly on the specific aircraft characteristics. This once more suggested that eventual successful thrust vectoring flight control must be realised by a fully integrated and optimised design from the outset (see summary of economic section).

Conclusions

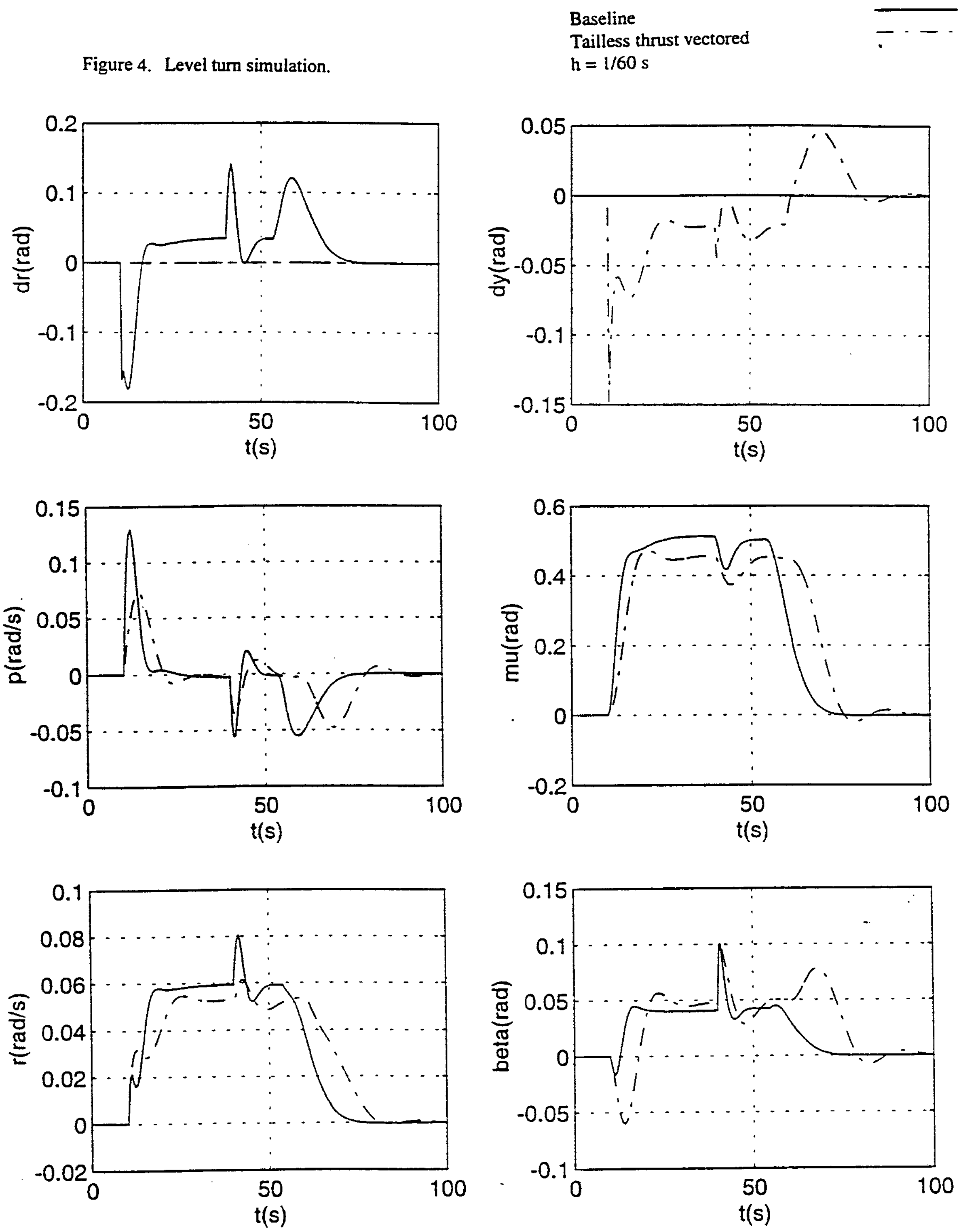
Civil applications of thrust vectoring were studied in order to provide a systematic overview of potential applications and consequences.

The necessary economic benefits are plausible to be realised only when thrust vectoring is integrated in new aircraft designs from the outset. All benefits depend strongly on the aircraft/engine configuration, with the currently common wing-mounted engine layout not being favourable. Best perspective is offered by thrust vectoring flight control with removed or downsized vertical tail sections.

Safety benefits were expected to be more feasible. Especially increased low-speed control and flight control system redundancy may prove beneficial. However, adverse safety aspects put forth severe requirements for thrust vectoring system reliability.

The thrust vectoring system can basically be adapted from developed military systems. Vectoring nozzles were established to be more suitable than tilt-engine systems or reaction control systems. When adapting military nozzles, main efforts must be directed to adapting to specific civil engine layout and system reliability.

Figure 4. Level turn simulation.



Finally, it was recommended to devote further efforts to:

- Study integration and optimisation of thrust vectoring in new aircraft designs.
- Study thrust vectoring applications for supersonic transports, which engines resemble military engines more closely.
- Study the suggested safety benefits in more depth.

Acknowledgements

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