Citation:

Marino, M, Fisher, A and Sabatini, R 2015, 'The effects of tube deformities on the dynamic calibration of a tubing system', in Proceedings of the 2nd IEEE International Workshop on Metrology for Aerospace (MetroAeroSpace 2015), United States, 4-5 June 2015, pp. 507-512.

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Version: Accepted Manuscript

Link to Published Version:

http://dx.doi.org/10.1109/MetroAeroSpace.2015.7180709

M. Marino, A. Fisher and R. Sabatini, “The effects of tube deformities on the dynamic calibration of a tubing system”, in proceedings of *IEEE International Workshop on Metrology for Aerospace (MetroAeroSpace 2015), Benevento, Italy, 2015.*

The effects of tube deformities on the dynamic calibration of a tubing system

Matthew Marino, Alex Fisher, Roberto Sabatini
RMIT University
School of Aerospace, Mechanical and Manufacturing Engineering
Melbourne, Australia

***Abstract* - Using the Berge and Tijdemen method for tube calibration is powerful as it allows for tubes of various dimensions to be used in a dynamic pressure data acquisition system by using post-processing methods to calibrate for the tubes natural dynamic response. Knowing the tubes response and using the inverse Fourier transform to calibrate the tube system is accepted however knowing how tube deformities influence this calibration is not known. Small singular deformities caused by pinch, twist and bending, which corresponded to a pinch and internal area ratios less than approximately 5 and 3.57 respectively, do not affect the tubing response of a system. Significant effects on the tubes response only occur at pinch and area ratios above these values. Furthermore, pinching ratios above 5 are extreme and represent a tube that is pinched locally to the point where it is almost blocked. This is testament to the tubes resilience to local and internal diameter changes. It can be safely assumed that unwanted and unexpected dampening of a tubing system could be due to a local tube deformity.**

Keywords – tube deformation; dynamic tube response; dynamic calibration; pressure sensing; pressure measurement.

I. INTRODUCTION

Measuring fluctuating pressures requires the adoption of multidisciplinary sensing and data analysis technique. The method of measuring surface pressures, by pressure tapping a surface and connecting it via sealed tubes to a remote transducer, is a technique which is extensively used in wind and aerospace engineering [1, 2]. Recent developments have been achieved in the area of Micro Air Vehicles (MAVs) where pressure variations are used to sense turbulence and to reduce, correct or mitigate its effects on MAV flight [3-7]. In common applications of wing pressure tapping, the location of the pressure transducer bank is significantly displaced from the location of the sensing taps. Thus, long tube lengths to connect taps to transducers are typically needed. The dimensions of the interconnecting tubes skew the dynamic response of fluctuating pressure and cause either resonance or viscous dampening. Therefore, we cannot assume that the pressure measured at the desired location is unaltered before it is read by the remote pressure transducer [8]. Where static pressures are measured at a very low acquisition rate ($f < 5$Hz), a calibration of the tubing system may not be required. However, if higher data acquisition rates are needed, the dynamic calibration of the tubing systems is essential to correct for the errors introduced.

Dynamic tube calibration is not a new topic with a number of well proven calibration methods used throughout the engineering disciplines. Additionally, improved methods of dynamically calibrating tube systems are currently emerging due to technology advancements. Tube manufacturing tolerances have shown to affect the dynamic calibration of a tubing system in amplitude and phase response. The manufacturing tolerance on the internal diameter is one of the key parameters that can significantly affect the amplitude response of a tubing system. Fig. 1 displays the amplitude variation using tubes with varying diameter and constant tube length.

The tubes commonly used for dynamic pressure measurements are typically made of rubber or plastic materials. As they are commonly placed in relatively small spaces/enclosures, they sometimes require to be woven, bent and guided through the aircraft structures in order to reach the bank of pressure transducers. As such the tubes are susceptible to bending and pinching, which can affect the dynamic calibration of the tubing system. In this research, tube pinching and associated internal diameter changes are shown to influence the tubes natural frequency response. This is done experimentally using a device that can supply a dynamic pressure signal to the tubes and then sensed by the pressure transducers.

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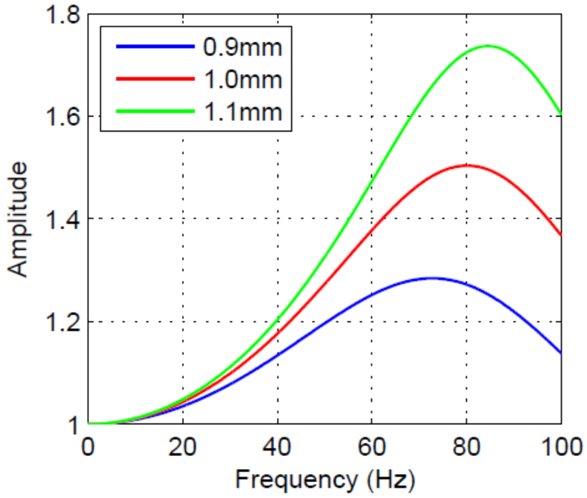

Fig. 1: Variation in amplitude response on a 750mm tube with different internal diameters [9].

II. DYNAMIC CALIBRATION METHOD

The Turbulent flow Instrumentation (TFI) software, used in these experiments, allows for calibration of time-varying pressures utilizing the Berge & Tijdemen tube correction method [1]. They derived the amplitude and phase response of multiple tubing systems with various geometric parameters using a modified version of the Navier-Stokes equations of continuity and state. The characterization of a tubing system allows for the Inverse Fourier Transform (IFT) to be applied to raw pressure data returning a tubing system to a flat frequency response in post processing. Similar experiments using the TFI Dynamic Pressure Measurment System (DPMS) system have been done with such calibration methods for data acquisition of time-varying pressures [10-12]. The estimated frequency and phase response for frequencies up to 100Hz are featured in Fig. 2. The Berge and Tijdemen tube calibration method was used to estimate the tube response of the interconnecting PVC tubes. Frequencies up to 200Hz are tested as higher frequencies lay beyond the range of interest, however tube correction was applied up to the Nyquist frequency of 1250Hz.

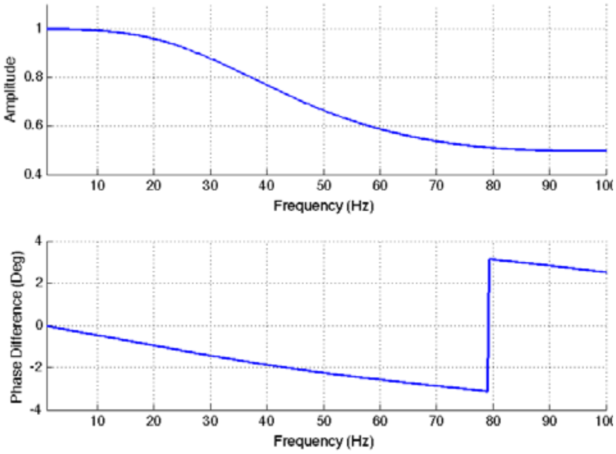

Fig. 2: Estimated Berge and Tijdemen frequency and phase response of tubes (L = 1600mm, $D_{internal}$ = 1mm).

III. DYNAMIC PRESSURE CALIBRATION DEVICE

To evaluate the accuracy of the approximated frequency response, a Dynamic Pressure Calibration Device (DPCD) was applied to each pressure tap on a wing used in research on the active stabilization of Micro Air Vehicles at RMIT University. The Dynamic Pressure Calibration Device was made by attaching a 40mm mylar cone to a small chamber with two ports to form a coupling camber. The 4mm port at the bottom of the chamber featured a rubber O-ring that was a flush fit against each pressure tap on the wing. A side port featured a 50mm PVC tube connecting to a separate pressure transducer channel and was used as a reference pressure signal free from tube bending, long tube length and tube diameter inconsistencies. The main port length was considered small (L = 4mm) in comparison to interconnecting PVC tubes and was assumed to have a constant uniform pressure and zero phase response.

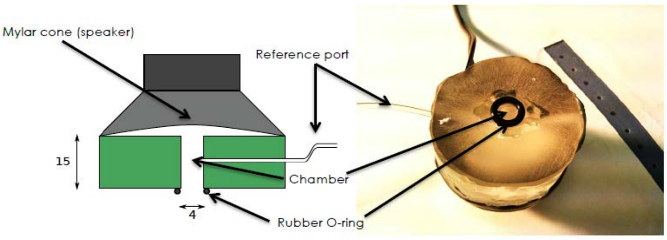

Fig. 3. The Dynamic Pressure Calibration Device (DPCD) device used for dynamic tube calibration.

To ensure the pressure at the reference port matches the pressure appearing at the tap, the distance between the two ports must be sufficiently small compared to the wavelength at

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the frequencies of interest. This condition was met with a distance to wavelength ratio of d/λ = 0.002. Although the frequencies of interest range from 0 to 100Hz, the system was sufficient to calibrate a tube for frequencies up to 2kHz.

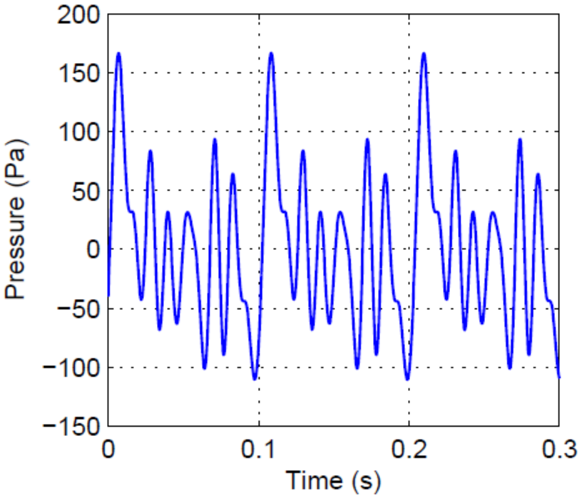

Fig. 4: The waveform used to drive the speaker [4].

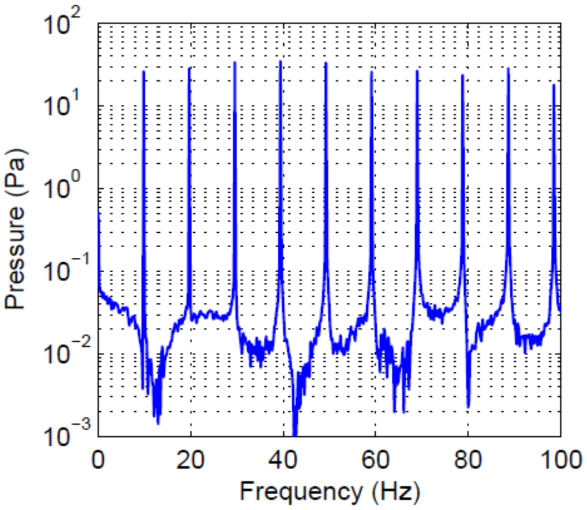

Fig. 5: Frequency response of the waveform proving the speaker.

The speaker was connected to a micro controller, which provided an amplified pulse-width modulated signal for 4 seconds to the speaker driver. A total of 10 pressure taps were calibrated by allowing the PCD to sit flush with each pressure tap to apply a periodic pressure consisting of a sum of 10 discrete frequencies. The pressure data obtained from each tap was subjected to a Fourier analysis where amplitude and phase response of the transfer function were obtained at each frequency. To evaluate the calibration skew, due to bending, some tubes where bent to a point where a kink was formed. Tubes were also squeezed to force significant change in the internal cross section area and shape. This is discussed in further detail in later sections.

IV. DYNAMIC RESPONSE VALIDATION

Fig. 6 displays the tubing response of 10 randomly selected pressure taps around the wing. Tube response for each tap was plotted against the theoretical Berge and Tijgeman tube response for comparison.

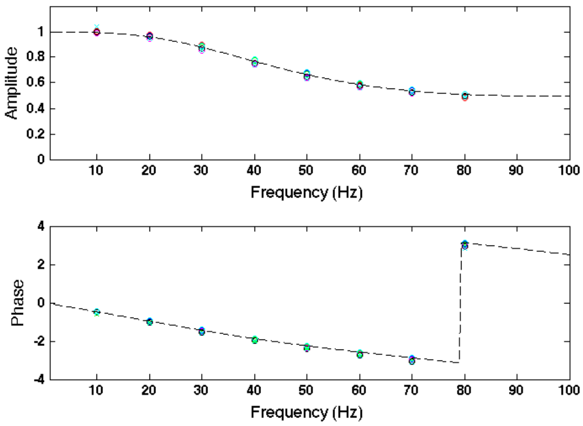

Fig. 6. Compartison betweent the theoretical and measured tube response of the 10 PVC tubes.

Variance between Berge and Tijgemen and experimental tube responses were measured to be +/- 2% for frequencies up to 80Hz. The small variation in internal tube diameter was assumed to be the likely cause of tube response error as it holds greatest sensitivity to tube response estimations (the 6th power) [1]. This variation was assumed to have negligible influence on the amplitude and phase response on the pressure acquisition system and was ignored in post processing of data. The application of the inverse Fourier transform in post processing returned the tubing response to a flat profile removing the attenuation effects of the tubes.

V. TUBE PINCHING

The sensitivity of tube response due to internal diameter is significant when we take the overall average of the tubes internal diameter. Changes to the internal diameter at specific locations and how this may skew the tubes frequency response is untested and published. In many-pressure tapping tasks lengths of tubes are routed between the source of measured pressure and a bank of pressure taps. Many tubes and routing complexities can encourage tubes to twist, kink and pinch at various locations across their length. These deforming features have the ability to alter the inter diameter and cross sectional area of the tube while skewing its natural frequency response.

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To avoid any adverse effects on the systems pressure sensing capability tube deformations are intentionally avoided. The degree of pinching can be quantified non-dimensionally using pinch factor calculated stated in equation 1.

$$P_r = \frac{R_i}{R_d} \qquad (1)$$

Where P_r is the pinch ratio, R_d is the diameter at the location of the pinch and R_i is the normal internal diameter of the tube.

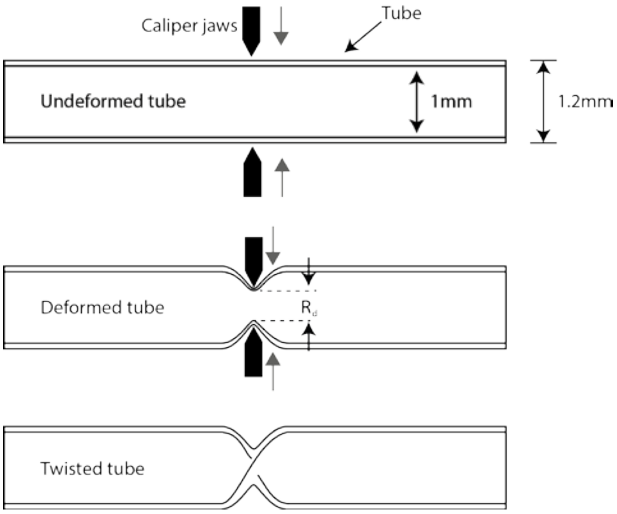

Fig. 7. Demonstrating the dimentions of the tube, the manner in which is it atrificaially pinched and how this simultes other deforming occurances such as tube twist.

Each pinch was artificially created by contracting the jaws of digital calipers to effectively “pinch” the tube. This allowed an accurate and repeatable method of pinching the tube with accuracy up to 0.01mm. The calipers are adjusted until the required pinch ratio is obtained (refer to Fig. 7). Once done the DPCD was used to supply dynamic pressure as explained in section 3. The frequency response of the pinched tube is directly compared to that of the normal tube of same length. It must be assumed that the reduction of tube wall thickness is negligible when the caliber load is applied.

Tube lengths of 1600mm, 1200mm, 800mm and 200mm were tested to assess whether cross sectional changes produce a consistent or variable influence on the frequency response of different tubes lengths. Controlled pinching tasks within the experiment change the inner diameter of the tube. Reduction of the internal diameter, pinch ratio, ellipse dimensions, internal area and area ration are detailed in table 1. Area ratio is calculated in the same manner as pinch ratio using:

$$A_r = \frac{A_i}{A_d} \qquad (2)$$

Where the area ‘A’ of the ellipse is calculated in the normal manner using:

$$A = \pi ab \qquad (3)$$

In order to calculate the area ratio both radii are needed. The effect of the pinching produces semi axes ‘b’ and ‘a’. In order to calculate the change in ‘a’ with respect to ‘b’ we use the ellipse circumference ‘C’ equation (Eqn 4)

$$C = 2\pi\sqrt{\frac{a^2+b^2}{2}} \qquad (4)$$

This can be transposed to acknowledge the semi axis minor as the subject.

$$a = \sqrt{2\left(\frac{C}{2\pi}\right)^2 - b^2} \qquad (5)$$

Ellipse circumference equation 4 is an imperial model where circumference is approximated within 5%. More complex models are available such as Ramanujan approximation method and the ellipse circumference infinite series.

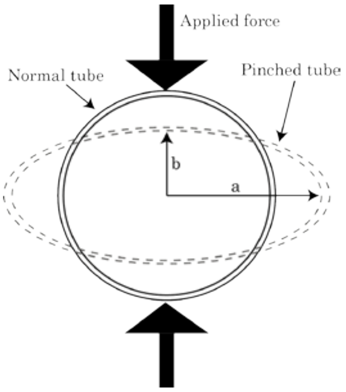

Fig. 8. The local change in internal tube dimentions due to an artificial pinch

Table. 1. The relationship between pinch ratio and tube speicifcation at location of pinch

Longitudinal internal diameter (2b)	b (mm)	a (mm)	Area (mm^2)	Pinch Ratio	Area Ratio
1	0.5	0.5	0.79	1.00	1.00
0.9	0.45	0.54	0.76	1.11	1.03
0.8	0.40	0.58	0.73	1.25	1.08
0.7	0.35	0.61	0.67	1.43	1.17
0.6	0.30	0.64	0.60	1.67	1.30
0.5	0.25	0.66	0.52	2.00	1.52
0.4	0.20	0.68	0.43	2.50	1.84

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0.3	0.15	0.69	0.33	3.33	2.42
0.2	0.10	0.70	0.22	5.00	3.57
0.1	0.05	0.70	0.11	10.00	7.14
0.08	0.04	0.71	0.04	12.5	8.80

The experimental matrix per tube length is outlines in table 1. Pinch ratios between 1 and 2.5 are tested. The tube was pinched mid length of each length of each tube. One end of the tube was interfaced with the DPMS while the other was exposed to the DPCD. The contact between the wing surface and the DPCD was flush at all times to eliminate leaking influences. The ratio of pinch ration to internal cross sectional area is shown in Fig. 9.

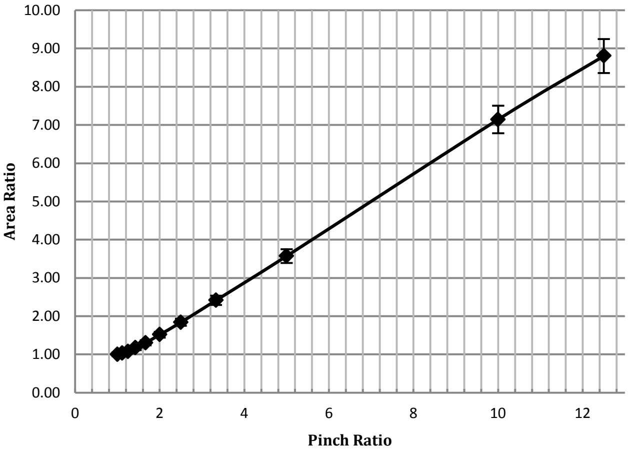

Fig. 9. Non-dimentional relationship between pinch ratio and internal corss section area ratio.

VI. EFFECTS OF TUBE PINCHING ON FREQUENCY RESPONSE

A series of 4 different tube lengths were tested using the DPCD. Each tube was subjected to various degrees of tube pinching in line with the test matrix summarized in table 1.

To reiterate an important point, various forms of tube deformities cause a change in the internal diameter of the tube at a specific location. To mimic this occurrence it is assumed that pinching tubes will reduce the internal diameter in a similar manner and similar a general case of local tube deformity. Pinch ratios from 1 to 12.5 were tested. Greater pinch ratios were not possible, as pinch ratios above 12.5 would block the tube entirely and seal the system.

The dynamic response of each tube was typical of single open-ended tubes at there respective lengths. Amplitude ratio gives a non-dimensional measure of the natural amplification and dampening, at each frequency, of the tubing system. Before the majority of the tests where conducted the tube was pinched at different locations across its length at pinching ratios of 1.25, 1.67 and 2.50. Each test produced identical results and proved that frequency response is not sensitive to the local location of tube pinching.

The pinch ratio for each length of tube was increased incrementally until a change in the tubes frequency response was noticed. Figures 9, 10, 11 and 12 display the frequency response for each tube tested.

The tube frequency response for pinch ratios up to 5 displayed no effect to the tubes frequency response up to the maximum frequency tested of 200Hz. Furthermore acceptable repeatability with a standard deviation less than 2% was calculated throughout the range of tested frequencies. This was also noticed when assessing the phase response of each tube.

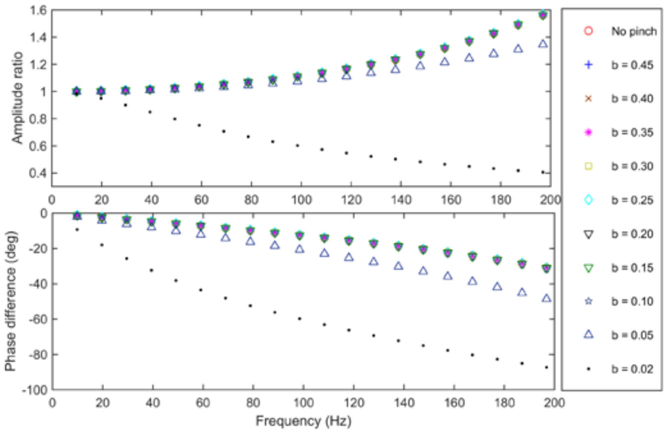

Fig. 10. 200mm tube frequency and phase response change with various degrees of tube pinching (in mm).

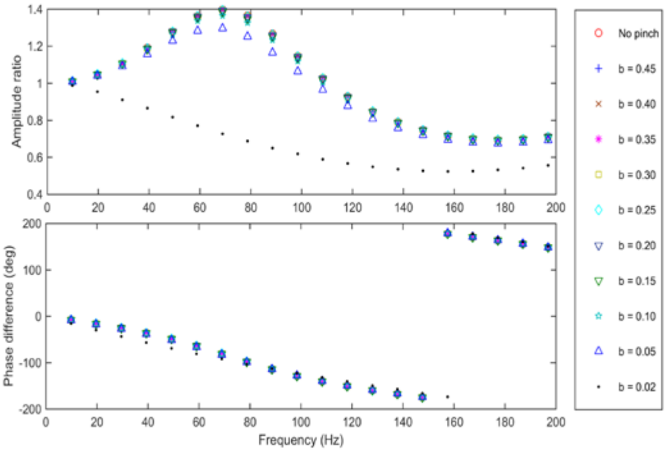

Fig. 11. 400mm tube tube frequency and phase response change with various degrees of tube pinching (in mm).

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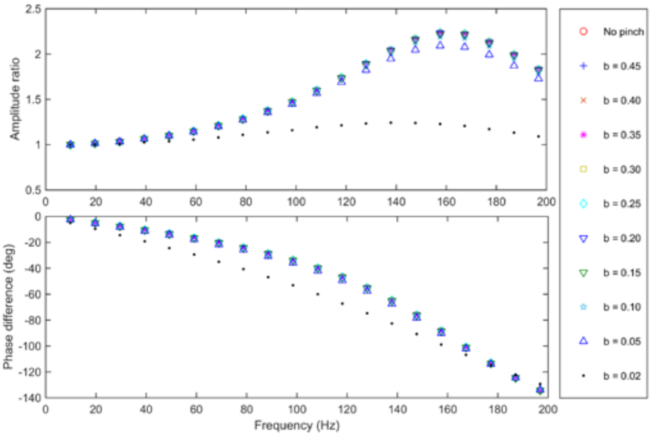

Fig. 12. 1600mm tube tube frequency and phase response change with various degrees of tube pinching (in mm).

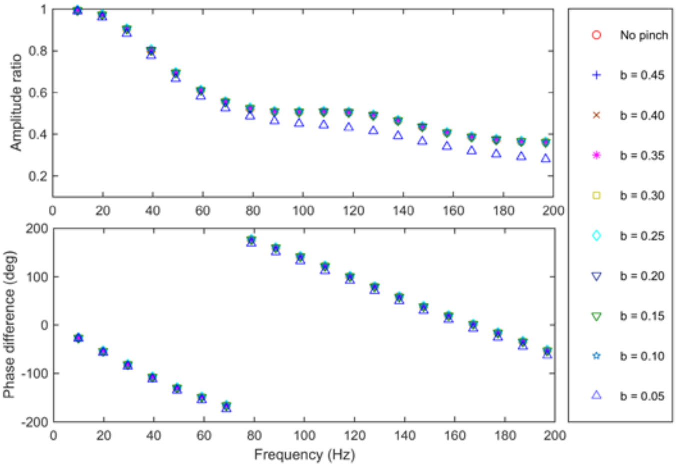

Fig. 13. 1600mm tube tube frequency and phase response change with various degrees of tube pinching (in mm).

Significant frequency response deviation was evident when the pinch ratio was increased to 10. This also corresponds to an area ratio of approximately 7.14. Under all circumstances the amplitude response is dampened. This dampening effect is more pronounced around the tubes first natural frequency as seen in tube lengths of 200mm, 400mm and 800mm. The tube length of 1600mm displayed a similar occurrence at its first natural frequency of 120Hz however the amplitude difference is not as pronounced.

It is also noticed that the frequency response difference is less than 5% for frequencies up to approximately 30Hz for all tube lengths. Furthermore the amplitude and phase difference up to 10Hz is not significantly skewed. For static and low frequency data-acquisition applications (f < 10Hz) highly pinched, kinked or twisted tubes could be used effectively.

At the extreme case, where pinch ratio is approximately 12.5 and the internal cross-sectional area has reduced by a factor of approximately 8.8, the frequency response per tube is significantly affected. For the tube length of 1600mm, the acquired signal was weak and produced an unusual frequency response across the frequency range. This was assumed to be an error within the post possessing software in its sensing algorithm. As such this was abstained from the plot as it held no additional information and detracted the papers merits.

It must also be noted although phase response was affected by the high pinch ratio, amplitude response was affected more so. This would suggest that the sound signal is still passing through the tube at the speed of sound however the pinch in the tube has the ability of reducing the energy within the sound wave. The amount of dampening is variable however maximized at the natural frequency. This could also be valid for the tubes high order harmonics however an extended range of frequencies must be tested to validate this.

VII. CONCLUSION

Although pinching has been recognized to affect the dynamic response of a tubing system, it is only significant (i.e., above the noise threshold) at the most extreme cases. The natural dynamics of the tube will change when the tube is almost to the point of being blocked. This gives testament to the resilience of the tubing system and can be assumed that a tubing system with a kink, twist or other external influence will not significantly influence the tube response. Measurements can be effectively taken under these circumstances. Furthermore, a theoretical tube correction method, such as the Berge and Tijdemen method, can be applied successfully. The deformation of a tube near full blockage will be noticeable in post processing as the dampening effects are significant for frequencies above 30Hz. It could be assumed that frequencies above 200Hz would be affected in the same way however further tests are needed to verify this hypothesis. One can assume that the material of the tube does contribute to the tubes resilience to deformities however this needs to be verified with further experiments. Future work will include similar tests with more than one pinch location to further assess the resilience of reducing the tubes internal diameter and increasing the applied reference frequency to the highest possible.

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4 DIMENSIONAL TRAJECTORY FUNCTIONALITIES FOR AIR TRAFFIC MANAGEMENT SYSTEMS

Alessandro Gardi[1], Roberto Sabatini[1], Trevor Kistan[1,2], Yixiang Lim[1,3] and Subramanian Ramasamy[1]
[1]RMIT University, Melbourne, Australia
[2]THALES Australia, Melbourne, Australia
[3]Imperial College London, London, UK

Abstract

The research presented in this paper focuses on the conceptual design of an innovative Air Traffic Management (ATM) system featuring automated 4-Dimensional Trajectory (4DT) Planning, Negotiation and Validation (4-PNV) functionalities to enable Intent Based Operations (IBO). In order to meet the demanding requirements set by national and international organisations for the efficiency and environmental sustainability of air transport operations, a multi-objective 4DT optimization algorithm is introduced that represents the core element of the 4DT planning functionality. The 4-PNV system interacts with airborne avionics also developed for 4DT-IBO such as the Next Generation Flight Management System (NG-FMS) on-board manned aircraft and Next Generation Mission Management System (NG-MMS) for Remotely Piloted Aircraft Systems (RPAS). In this article we focus on the 4-PNV algorithms, and specifically on the multi-objective 4DT optimization algorithm for strategic and tactical online operations. Simulation case studies are carried out to test the key system performance metrics such as 4DT computational time in online tactical Terminal Manoeuvring Area (TMA) operations.

Introduction

Large-scale aviation modernisation initiatives including the Next Generation Air Transportation System (NextGen) and Environmentally Responsible Aviation (ERA) programs in the US, and the Single European Sky Air Traffic Management Research (SESAR) and Clean Sky Joint Technology Initiative for Aeronautics and Air transport in Europe have been established to improve the operational efficiency, safety and environmental sustainability of aviation. As part of these and other national and international initiatives, a number of innovative operational and technological concepts have been identified for deployment in the civil aviation domain over the next decades [1-6]. The programmes prescribe the evolution of Air Traffic Management (ATM) into a highly automated, integrated and collaborative system, allowing a more predictable, flexible and efficient management of the airspace resources through higher levels of information sharing, automation and more accurate navigation. A number of technological enablers are required to introduce these innovations in the operational domain and to exploit their full potential. The foreseen evolutions will impact, in particular, the Communication, Navigation, Surveillance, ATM (CNS/ATM) and Avionics (CNS+A) systems context. In this perspective, the introduction of 4-Dimensional Trajectories (4DT) in an Intent-Based-Operations (IBO) environment was identified as a key step to enhance the operational efficiency, cost-effectiveness and environmental sustainability of aircraft operations.

System Design

New ground-based and airborne CNS+A systems are required to assist the human ATM operators and flight crews in planning, reviewing and validating the most suitable 4DT intents in a timely manner, while exploiting the substantially increased levels of airspace, weather and traffic information that will be shared among all stakeholders. In this perspective, earlier studies addressed the development of automated ATM functionalities [7-17]. The CNS+A systems implement 4DT Planning, Negotiation and Validation (4-PNV) algorithms, datalink communications enhanced navigation and surveillance technologies, integrity monitoring and augmentation systems, as well as suitable interfaces/processing to enable automated negotiation and validation of the aircraft intents for greener air traffic operations. Some of the initial 4DT-IBO technologies start approaching the market already, while early stage advancements in the juridical framework are accommodating some levels of

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enhanced operational capabilities. The research presented in this paper aims to develop an innovative 4-PNV ATM system that implements in a viable form the key operational and technological innovations identified by the major global aviation research initiatives. This paper expands the development of the ground-based 4-PNV system [18-23], which is a substantially innovative evolution intended to introduce online 4DT management functionalities including a complete multi-objective 4DT optimization algorithm.

Design Drivers

The design of the new automated ground-based and airborne CNS+A systems is driven by a number of requirements, presented below.

- **User-Preferred Trajectories**: the systems shall enable aircraft to fly user-preferred optimal trajectories, as far as practicable from the airspace, weather and traffic perspectives. For this reason, a fundamental aspect is represented by negotiation and validation functionalities, whose effectiveness largely dictates how much of the original user intents can be accommodated.
- **Operational Timeframes**: a timeframe convention for this research was introduced in [20]. The research focuses in particular on the online context (i.e., when the flight mission is active), which is traditionally considered more technologically challenging as it poses strict requirements in terms of a timely and consistent identification of an adequate 4DT solution for each aircraft. Furthermore, the software systems and algorithms under development are conceived to improve the efficiency and sustainability of air traffic operations in presence of disruptions that could not be predicted in the offline context (i.e., before the beginning of the mission).
- **Human Factors**: the systems shall minimize the workload and maximize the situational awareness of the human operators, by limiting the intervention of flight crews and Air Traffic Control Operators (ATCO) to high added-value tasks such as higher-level decision-making, monitoring, supervision and emergency decisions.
- **Resilience to Uncertainties**: the systems shall exploit all the information that can be shared between the ground and the aircraft in order to maximize the predictability of future traffic states and react to the occurrence of unpredicted events in a timely manner, so to minimize their impacts. Moreover, the algorithms should stochastically assess the potential deviations to enable an expert selection of confidence levels and associated safety margins.
- **4DT Validation**: the systems shall consistently identify solutions that fulfil the regulatory traffic separation criteria, the active airspace restrictions, and the aircraft performance limitations at all times. In particular, the computationally generated 4DT shall be assessed in terms of the lateral, vertical and longitudinal traffic separation criteria, airspace capacity and routing restrictions, as well as hazardous weather avoidance.
- **Mixed Fleet/Mixed Equipage**: the new CNS+A systems will be deployed gradually and progressively across the various Air Navigation Service Providers (ANSP) and aircraft fleets. Therefore, substantial levels of compatibility and interoperability with previous generation systems and procedures shall be entailed.
- **Dense Traffic**: the CNS+A systems shall consistently identify valid 4DT solutions even in the presence of dense air traffic severely limiting the feasible solution set.
- **Multi-Capability**: the systems shall be able to plan, negotiate and validate 4DT intents in all possible ATM instances.
- **Global Air Traffic Optimality**: the system should not attempt to accommodate the best 4DT intents of each aircraft individually, but instead perform an expert selection of the 4DT intents so to improve the overall optimality of air traffic in terms of the selected environmental and economic sustainability objectives.

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- **Offline Operations**: most of the aforementioned objectives associated with online operations are effectively stricter than the equivalent ones for offline 4DT planning. Therefore, the planned extension of the 4-PNV system to offline operations will initially rely on the same model-set and algorithms used for online operations. Future research will assess the need for dedicated algorithms.

System Architecture

Fig. 1 depicts a schematic architecture of the 4-PNV system.

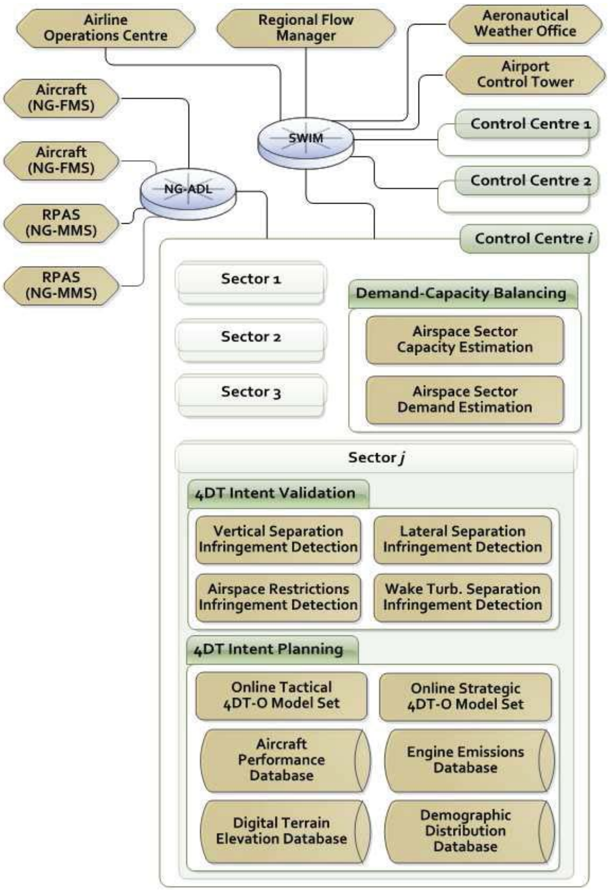

Figure 1. 4-PNV architecture

The online processes are distributed across the NG-FMS/NG-MMS, the Airline Operations Centres (AOC), the Air Navigation Service Providers (ANSP), the regional Air Traffic Flow Management (ATFM) centres and the ground-based ATM infrastructure. The ground-based ATM infrastructure is distributed among a number of Area Control Centres (ACC) and secondary facilities. Each centre/facility *i* is typically tasked with the tactical control of a number of airspace sectors *j*, as well as some level of strategic flow management and airspace management duties. The 4-PNV is designed as a distributed and decentralized computational Decision Support System (DSS) deployed in each centre *i* to assist the human operators while handling different strategic ATFM and tactical ATM roles.

Trajectory Optimization

A number of operational aspects and environmental impacts associated with the aircraft mission have significant dependencies on the flown trajectory. Trajectory optimization is, from an ATM perspective, the identification of the most suitable 3D/4D trajectory from the origin to the destination, based on dynamics/airspace constraints and user preferences, as well as meteorological and traffic conditions. Therefore, the adoption of computational algorithms for trajectory optimization represents a substantial evolution from the conventional flight planning methodologies currently in place and their associated limitations. From an operational perspective, since the offline flight plan is submitted as a substantially static entity, unforeseen weather and air traffic scenarios have the effect of progressively compromising its optimality. Another major limitation of conventional flight planning is due to the very narrow set of optimality criteria and their limited modelling, which do not encompass the full set of environmental impacts associated with aircraft operations. Currently, most of the noxious emission such as carbon monoxide (CO), nitrogen oxides (NO_X) and unburnt hydrocarbons (UHC) are addressed by operational aircraft piloting recommendations, while the minimization of fuel consumption implicitly ensures a minimization of carbon dioxide (CO_2) emissions. Noise emissions are currently mitigated through a careful design and redesign of Area Navigation (RNAV) departure and arrival procedures. As this is a static approach in reducing the amount of perceived noise, it is subject to uncertainties associated with severe weather or traffic perturbations in the online context. Growing R&D efforts are therefore addressing practical implementations of noise models in novel airborne and ground-based CNS+A systems. As part of this research, customized algorithms are being developed

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for the optimization of flight trajectories with respect to multiple objectives, while encompassing constraints that also entail strategic and tactical ATM and Air Traffic Flow Management (ATFM) directives as well as airspace The multi-objective optimisation suite comprises a number of models including the weather model, operational costs model, emissions model, airspace model, contrails model and noise model. The databases used in conjunction with the noise model are the demographic distribution and digital terrain elevation databases. The currently employed 4DT optimization algorithms are based on direct methods of the global orthogonal collocation category.

Aircraft Dynamics

The adopted three degrees of freedom (3DOF) point-mass dynamics model with variable mass is:

$$\dot{\boldsymbol{x}} = \begin{cases} \dot{v} = \dfrac{\tau \cdot T_{CL} - D}{m} - g \sin\gamma \\ \dot{\gamma} = \dfrac{g}{v} \cdot (N \cos\mu - \cos\gamma) \\ \dot{\chi} = \dfrac{g}{v} \cdot \dfrac{N \sin\mu}{\cos\gamma} \\ \dot{\phi} = \dfrac{v \cos\gamma \sin\chi + v_{w_\phi}}{R_E + z} \\ \dot{\lambda} = \dfrac{v \cos\gamma \cos\chi + v_{w_\lambda}}{(R_E + z)\cos\phi} \\ \dot{z} = v \sin\gamma + v_{w_z} \\ \dot{m} = -FF \end{cases} \tag{1}$$

Where v is the true airspeed, $\boldsymbol{v_w}$ is the wind velocity vector, γ is the flight path angle, χ is the track angle, m is the aircraft mass, ϕ λ and z are respectively the geodetic latitude, longitude and altitude, g is the gravity acceleration, R_E is the geodetic Earth radius, D is the aircraft drag, T_{CL} is the maximum climb thrust. The control variables are $\boldsymbol{u} = \{N, \tau, \mu\}$, which respectively represent the load factor, the throttle and the bank angle. The drag is calculated with the conventional parabolic approximation as:

$$D = \frac{1}{2}\rho v^2 S C_{D0} + \frac{2 C_{D2}\, N^2\, m^2\, g^2}{\rho\, v^2\, S} \tag{2}$$

Where ρ is the local air density, and S, C_{D0}, C_{D2} are obtained by the Eurocontrol’s Base of Aircraft Data (BADA) database and respectively represend the aircraft reference area and the two parabolic drag coefficients. The drag coefficient increases to account for flaps and landing gear are also available [24]. Adopting the formulation from BADA, the maximum climb thrust and the fuel flow of a turbofan engine are calculated as [24]:

$$T_{CL} = C_{T1} \cdot \left(1 - \frac{H_P}{C_{T2}} + C_{T3} \cdot H_P^2\right) \cdot [1 - C_{T5} \cdot (\Delta T - C_{T4})] \tag{3}$$

$$FF = \max \begin{bmatrix} \tau \cdot\ C_{f1} \cdot \left(1 + \frac{v_{TAS}}{C_{f2}}\right), \\ C_{f3} \cdot \left(1 - \frac{H_P}{C_{f4}}\right) \end{bmatrix} \tag{4}$$

Where $C_{T1} \ldots C_{T5}$, $C_{f1} \ldots C_{f4}$ are the thrust and fuel flow coefficients from the BADA empirical models [24]. The emission of a generic Gaseous Pollutant (GP) is modelled as:

$$GP = \int_{t_0}^{t_f} EI_{GP} \cdot FF\, dt \quad [\mathrm{Kg}] \tag{5}$$

The dependence of carbon monoxide (CO) and unburned hydrocarbon (HC) emission indexes on the throttle setting is empirically modelled as:

$$EI_{CO/HC} = c_1 + \exp(-c_2 \tau + c_3) \quad \left[{}^{\mathrm{g}}/_{\mathrm{Kg}}\right] \tag{6}$$

Similarly, the nitrogen oxides (NO$_X$) emission index is empirically modelled as:

$$EI_{NO_X} = c_1\, \tau^2 + c_2\, \tau + c_3 \quad \left[{}^{\mathrm{g}}/_{\mathrm{Kg}}\right] \tag{7}$$

Eq. 6 and 7 are developed to introduce an accurate nonlinear fit of the ICAO Emissions Databank [25], as detailed in [22]. The fitting parameters $c_{1,2,3}$ accounting for the CO emissions of 165 currently operated civil turbofan engines are $\boldsymbol{c} = \{0.556,\ 10.21,\ 4.068\}$ for CO, $\boldsymbol{c} = \{0.083,\ 13.2,\ 1.967\}$ for HC and $\boldsymbol{c} = \{7.32,\ 17.07,\ 3.53\}$ for NO$_X$. Linearized models can be introduced to enhance computational performance when required.

Weather Model

Diversions around unpredicted hazardous weather cells and extensive flight periods in regions of headwind or crosswind conditions have substantial negative effects on all environmental and economic performances of a flight, in addition to causing delays that perturb operations and negatively impact passenger satisfaction. Furthermore, many of the

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models introduced in the trajectory optimization framework require accurate local atmospheric data as input. For all these reasons a suitable weather model is a fundamental component of trajectory optimization software frameworks. A macroscale model can provide the global distributions of pressure, temperature, winds aloft, and relative humidity, which are essential inputs for the contrail model. Higher resolution models working at smaller scales provide information about the cloud-base and visibility, the occurrence and dynamics of dangerous clouds, precipitations, fog and haze, clear air turbulence, wind shear and microbursts. The model currently employed processes the global weather data available from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA), and selectively extrapolate the required information on a structured 4D grid. The data currently employed is extracted from the Global Forecast System (GFS), collected on a 0.25° latitude and longitude resolution grid, updated every 6 hours (4 times daily), and including projection of up to 180-hours in 3-hours intervals. Fig. 2 and Fig. 3 represent the results of the developed weather model for a 15-hour advance forecast of wind, temperature and relative humidity 4D field sampled at 0600 UTC of April 3rd 2015.

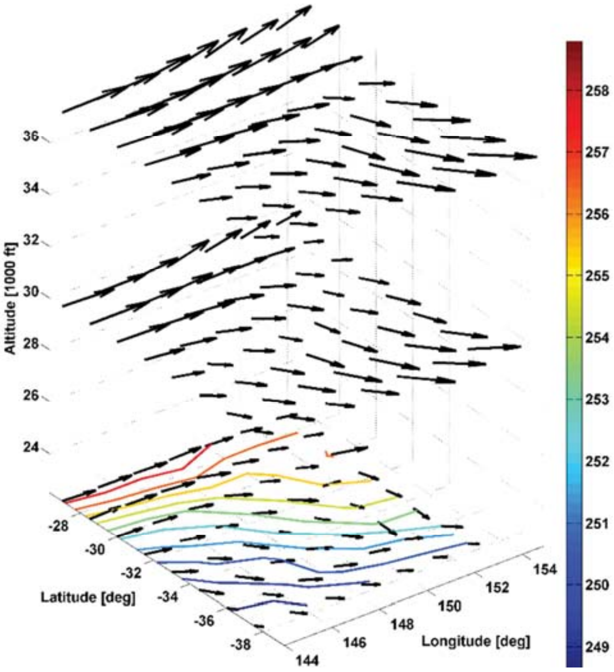

Figure 2. Wind and temperature 4D fields

Whenever interpolation is performed upon the original NCDC GFS data, the following expression (known as barometric formula) is adopted for the vertical trends:

$$\frac{P}{P_0} = \left[\frac{\mathrm{T}_0}{\mathrm{T}_0 + L\,(h - h_0)}\right]^{\frac{g}{L\cdot R^*}} \quad (8)$$

where P is the extrapolated pressure, P_0 and T_0 are reference pressure and temperature, h and h_0 are the altitude of extrapolation and reference points, L is the locally evaluated lapse rate and R^* is the specific gas constant for air.

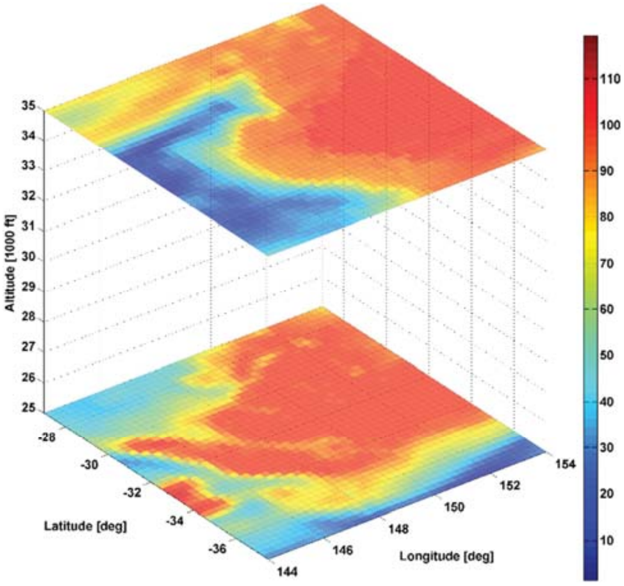

Figure 3. Relative Humidity 4D field

Multi-Objective Optimality

In line with the requirements for online tactical replanning, the weighted sum method, belonging to the category of *a priori* articulation of preferences, is adopted for the pre-identification of a combined performance index J [20, 26]. The a priori multi-objective optimisation approach is conceptually represented in Fig. 4. The performance weightings can be dynamically modified along the flight and as part of an ongoing Collaborative Decision Making (CDM) process between the AOC and ANSP when required. Multiple optimal 4DT are generated on board each traffic, and then using a rule-based algorithm, a conflict free set of trajectories is found for all aircraft.

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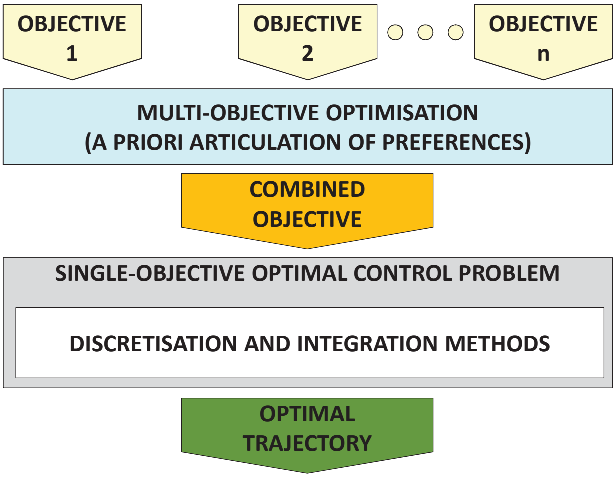

Figure 4. Block diagram of multi-objective optimisation with a priori articulation of preferences [20]

4DT Optimisation Algorithm

The numerical algorithm for the solution of the optimal control problem with respect of the combined objective resulting from the weighted sum a priori articulation of preferences is represented in Fig. 5. A mathematically optimal 4DT is generated by means of a numerical solver based on a direct method of the family of global orthogonal collocation (pseudospectral). This 4DT is a discretised version of a Continuous/Piecewise Smooth (CPWS) curve, which in general may not be flyable by human pilots nor by conventional Automatic Flight Control Systems (AFCS), as it includes transition manoeuvres involving multiple simultaneous variations in the control inputs. Moreover, the discretised CPWS consists of a very high number of overfly 4D waypoints, which would have unacceptable impacts on the Next-Generation Airborne Data-Link (NG.ADL) bandwidth usage. Therefore, a post-processing stage is introduced, which employs manoeuvre identification algorithms to segment the trajectory in feasible flight legs, including straight and level flight, straight climbs and descents, level turns, and climbing/descending turns. The final result is a concisely described 4DT consisting of feasible flight segments.

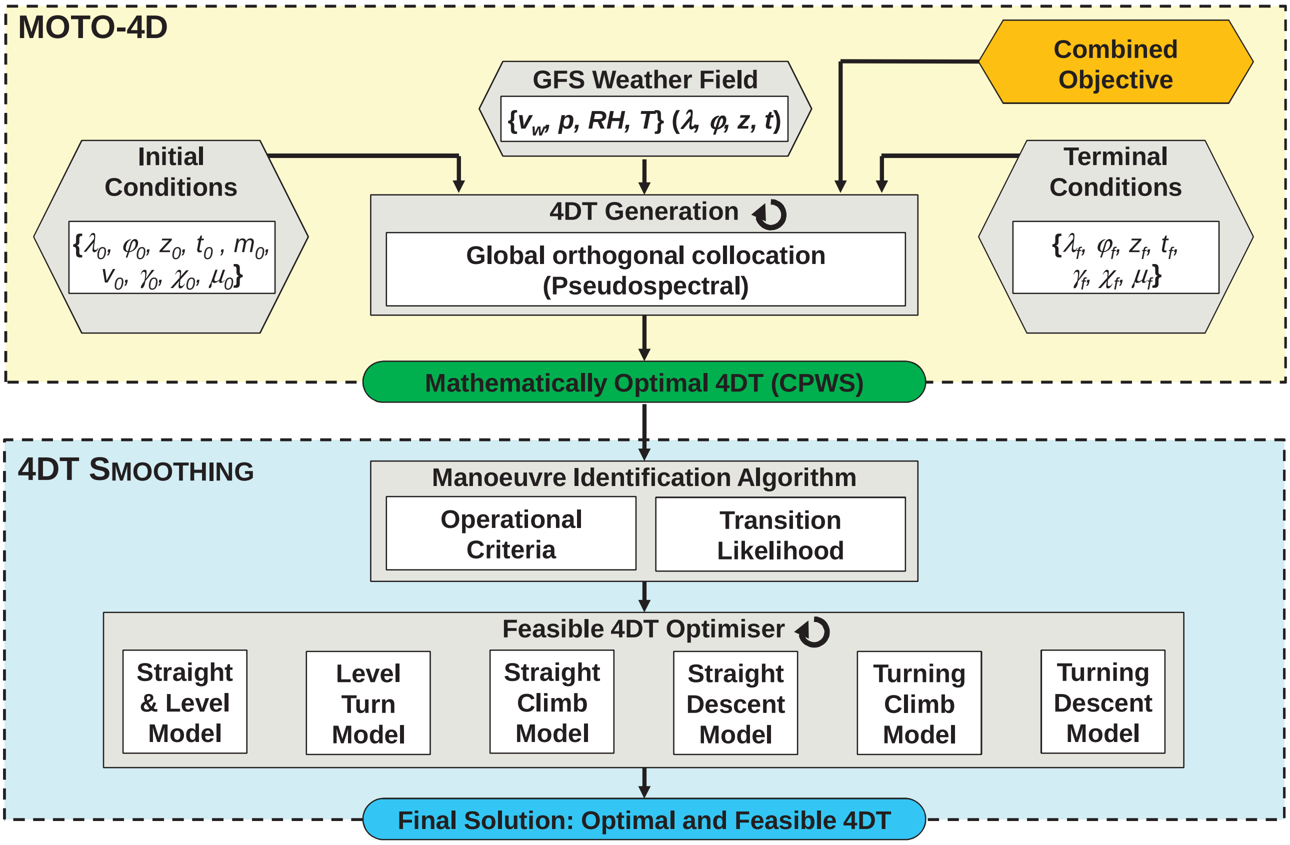

Figure 5. Block diagram of the 4DT optimisation algorithm

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Negotiation and Validation

Negotiation and validation algorithms were developed to meet the stringent time requirements for strategic and tactical online operations. A *single-attempt* negotiation is required in order for the 4-PNV to meet the online tactical rerouting requirements. In order to be adopted for both strategic online and tactical online contexts, with a reference time horizon of 3 minutes, it is required that the total duration of optimization, negotiation and validation processes must remain under 180 seconds. Our customized negotiation loops originally based on EUROCONTROL’s DOC 97-70-14 [7] were introduced in [19] and are depicted in Fig. 6 and Fig. 7, which respectively represent the 4-PNV initiated and the NG-FMS initiated loops. The shared 4DT intents include the aircraft’s unique identification and model, the wake-turbulence category, and the vector of 4DT segments. The 4-PNV system is the protagonist of the strategic online scenario as it retains a continuously updated global situational awareness. Unpredicted events prompt the 4-PNV to initiate a strategic replanning and negotiation by uplinking new constraints to the NG-FMS, triggering on-board 4DT optimization. Alternatively, the 4-PNV may compute optimal 4DT and uplink them for validation by the aircraft. If, after on-board validation, constraint violations are detected (e.g. turn radius, climb rate), the aircraft downlinks a rejection message together with a new intent. Multiple negotiation loops are allowed in the strategic online scenario but minimized thanks to the availability of multiple intents for each aircraft. In the tactical online scenario, either the NG-FMS or the 4-PNV may initiate intent negotiations. The 4-PNV will act mainly as a key decision maker. The NG-FMS may initiate the negotiation due to locally detected weather changes, aircraft performance degradation, equipment failures or on-board emergency situations. Other manoeuvre-related factors such as inefficient heading changes, and unachievable climb/descent rates and altitudes due to the actual aircraft weight may also be causes of negotiation. In the tactical online scenario, a “single-loop” negotiation is ultimately sought due to the reduced time and stringent traffic management commitments.

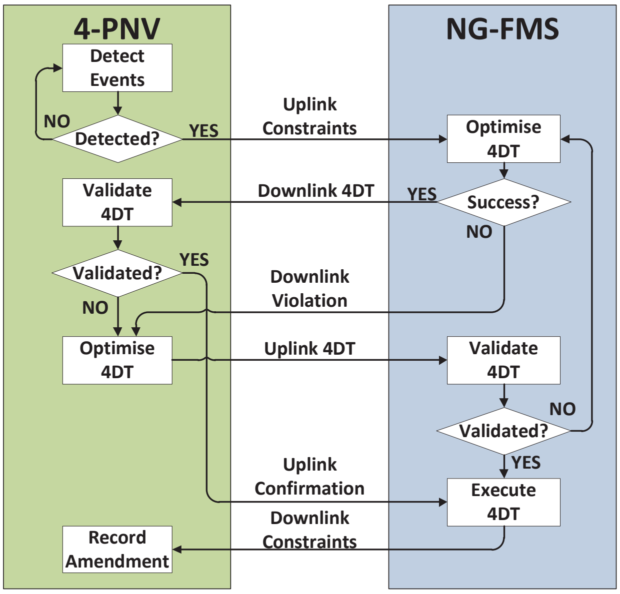

Figure 6. 4-PNV initiated 4DT Intent Negotiation/Validation Loop

4DT are checked for traffic conflicts and separation from hazardous phenomena. The validation algorithm assesses the lateral and vertical separation criteria and includes a simplified wake vortex modelling to assess the longitudinal separation.

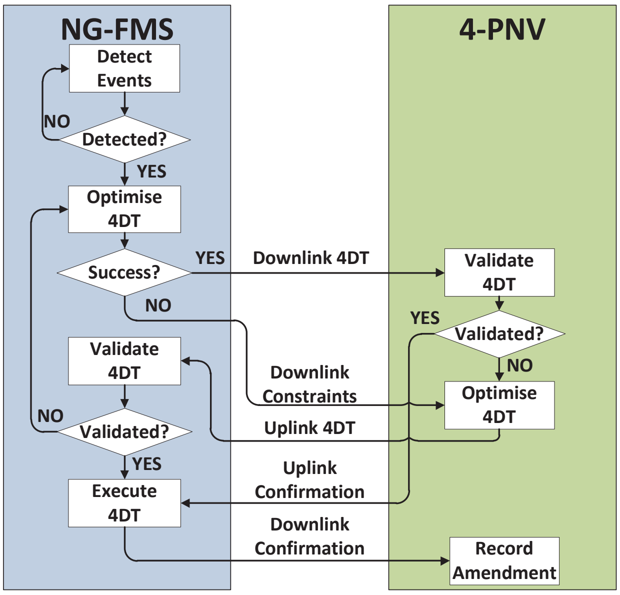

Figure 7. NG-FMS initiated 4DT Intent Negotiation/Validation Loop

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Air Traffic Flow Management

Traditional ATM automation systems provide some level of support for implementing Air Traffic Flow Management (ATFM) measures, particularly during the tactical phase of operations. Emerging ATFM Decision Support Systems (DSS) provide additional capabilities, including:

- Common situational awareness, including display of weather, aeronautical messages, constraints, etc.
- Demand prediction based on scheduled, filed or live traffic data and/or analytical estimation/numerical simulations [27].
- Graphical representation of traffic (air situation display) and load (bar charts or similar).
- Fast-time simulation and “what-if” modelling of ATFM measures.
- CDM communication mechanisms (increasingly web-based).
- Compliance reporting and post-event analysis.

Major areas of research for ATFM DSS include Human Machine Interface and Interaction (HMI^2) techniques to visualise complexity and dynamic density concepts, merging metering with sequencing, i.e. the integration with Arrival and Departure Management (AMAN/DMAN) operations, and the development of regional ATFM concepts that support multiple ANSP. From the specific Demand-Capacity Balancing (DCB) measures listed above, it can be observed that ATFM addresses predominately demand-side issues; the ability to modify capacity-side factors is currently limited to strategic and pre-tactical measures. This limitation is addressed by introducing Dynamic Airspace Management (DAM) functionalities. Both ATFM and DAM algorithms are currently being researched and evaluated within the 4-PNV system and in concurrent research activities [21].

Simulation and Results

The sequencing of dense arrival traffic towards a single final approach segment was extensively evaluated as a representative case study of online tactical Terminal Manoeuvring Area (TMA) operations [20]. The 4-PNV identifies the best arrival sequence among the available options. Longitudinal separation is enforced at the merge-point to ensure sufficient separation upon landing, and to prevent separation infringements in the approach phase itself. The 4-PNV is capable of performing point-merge at any metering point. After the initial intents have been stored in the 4-PNV, the point-merge sequencing algorithm allocates the available time slots accordingly. The assumed minimum longitudinal separation is 4 nautical miles on the approach path for medium category aircraft approaching at 140 knots, therefore the generated time slots are characterized by a 90~160 seconds separation depending on the wake-turbulence categories of two consecutive traffics. The results of one representative simulation run are depicted in Fig. 8. Fig. 9 depicts the computed 4DT in the AMAN schedule display format. Waypoints and lines depicted in magenta represent the flyable and concisely-described 4DT consisting of a limited number of fly-by and overfly 4D waypoints, obtained through the smoothing algorithm.

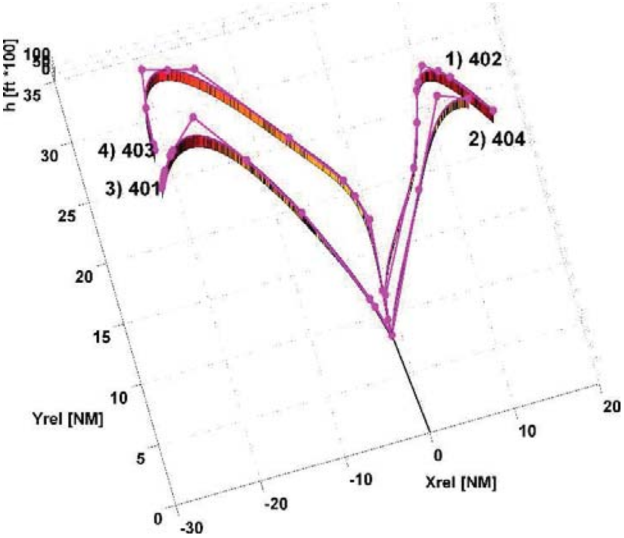

Figure 8. Results of the 4-PNV in the AMAN scenario

Monte Carlo simulation was performed, resulting in an average of 41 seconds for single newly generated 4DT intents, and consistently less than 60 seconds. The 4DT post-processing allowed to reduce discretised CPWS trajectories of 150 to 450 points into a number of fly-by and overfly 4D waypoints consistently below 20. These results meet the set

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design requirements for tactical online data-link negotiation of the 4DT.

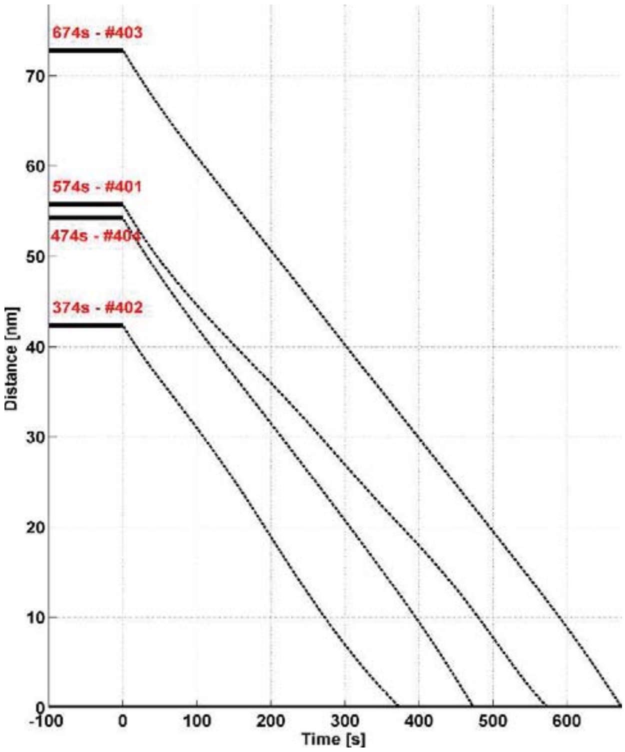

Figure 9. AMAN Schedule plot of the resulting 4DT

Conclusions

This paper presented the conceptual design of a novel 4-Dimensional Trajectory (4DT) Planning, Negotiation and Validation (4-PNV) system, conceived to introduce automated Air Traffic Management (ATM) functionalities in strategic and tactical online operations. The 4-PNV system is intended to operationally enable 4DT Intent Based Operations (IBO) in synergy with the Next Generation Flight Management System (NG-FMS) on board manned aircraft and Mission Management Systems (NG-MMS) for Remotely Piloted Aircraft Systems (RPAS). Simulation case studies allowed a preliminary assessment of the 4-PNV negotiation and validation models. In high air traffic density conditions, the complete process of NG-FMS/MMS 4DT intent generation, downlink to the 4-PNV and negotiation/validation is performed in less than 180 seconds. These results meet the 3 minutes timeframe assumed for online tactical routing/rerouting tasks and make the approach feasible for the intended applications. Future research will address the implementation and evaluation of other indirect and hybrid trajectory optimization methods, as well as enhanced algorithms for conflict detection. The concurrent research on safety-critical obstacle avoidance and Detect-and-Avoid (DAA) systems will be highly instrumental in the implementation and assessment of efficient optimization models for 4DT planning [28-32]. Reduced separation minima will be implemented to exploit the full potential of high-accuracy advanced Navigation and Guidance Systems (NGS) [33-36]. The 4-PNV evolutions will also incorporate various CNS+A integrity monitoring and augmentation strategies currently being researched [37-40].

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