Chapter 1

Introduction

A generic utility helicopter of conventional configuration with main and tail rotor is considered. Several realizations of $\mathcal{L}_1$-control for attitude and vertical speed control are shown. A high-fidelity simulation in place of a real helicopter serves as research platform, treated as gray-box simulation. Publications of preliminary results are: [1], [2], and in particular the baseline controller: [3] (the author's diploma thesis).

1.1 Motivation

If the plant dynamics and their changes are not sufficiently well known, adaptive elements may be desirable. A controller is aimed at that contains explicitly the predefined desired dynamics, wherein tracking is done adaptively. In addition, the desired dynamics need to be provided with mechanisms to ensure feasibility, that is to account for time delays, input saturations, and the limited input channel bandwidth – present in any physical system. The combination of feasible desired dynamics with an adaptive tracking strategy holds out the prospect of two major benefits:

1. Maintaining handling qualities in adverse conditions and thus enhancing survivability;
2. Reducing the development effort;

Survivability of the helicopter in this context reduces most notably to maintaining handling qualities. It may be questionable whether keeping a helicopter aloft in case of severe damage is significantly more likely with a different controller structure. It is of particular interest

however to *maintain handling qualities* in DVEs (degraded visual environments), MTEs (mission task elements) with divided attention e.g. delivering or picking up loads, or combat situations – in general operating near ground. For avoiding obstacles, predictable behavior of the vehicle is crucial, especially in military operations, where flying very low and fast is a frequently applied tactic to escape hostile fire. If degraded performance cannot be avoided, pursuing dynamics scaled to a lower bandwidth may be the best option. This means keeping the same behavior (e.g. linear, first order) but with different velocity (i.e. gain or bandwidth).
Furthermore, in some situations loss of control can be prevented only in a very short time window. A fast acting controller as well as retaining handling qualities for a safe recovery are crucial, especially in the inner loop. A vehicle suddenly and without clear warning degrading from Level 1 to Level 3 on the Cooper Harper Rating Scale is believed to be worse than an aircraft being Level 3 from the beginning.

Helicopter dynamics are complex even without any failure and finding a linear design point may be elusive, e.g. for the asymmetric, weak and time varying directional stability. Another example of dynamics, that are hard to capture and hardly quantifiable, are cross-couplings. For these cases, an adaptive model following strategy can be helpful and simplify the design procedure to meet the increasing requirements of recent safety specifications.

Figure 1.1: An Mi-24 (Photo from the author's collection)

This tempts to aim at a care-free handling approach as it is practiced with unstable fighter jets, this however can be accompanied by an unreasonable high effort – if possible at all – for helicopters. Automating the prediction of the vortex ring state or the pitch-up phenomenon reliably for example can be tedious up to impossible, leaving it to pilot training to avoid it. Given the fact that escaping the flight envelope can normally be averted but the risk is impossible to be eliminated, recovery from these conditions back into the normal operational flight envelope is a desirable capability of the controller. When encountering enemy fire, no pilot can be expected to stick to low-frequency inputs or safe flight strategies.

The second point has obvious benefits also beyond manned civil planes. Cutting costs in the controller development may be attractive for the low-cost UAV industry, for instance.

An adaptive model following controller may be utilized as cross-platform controller for many types of helicopters. Then, tuning reduces to adjusting the implemented model of the input channel as well as the desired closed-loop performance specified in the predictor. This may be realized by a conservative choice of the desired performance, expected to be within robustness margins for an entire class of helicopters. However, the new methodology does not relieve of the required understanding of the *helicopter's* peculiarities and performance bounds.

1.2 Controller Requirements and Objectives

From modern adaptive controllers, fast adaptation, reasonable design effort, and sufficient time delay margin representing robustness are expected. Performance, in particular in the transient, is required to be deterministic and locally guaranteed. The controller is applicable to analysis of safety-critical systems, a fact that imposes strict conditions on functionality and reliability.

The Choice of Linear Desired Dynamics

Linear low order systems are considered easy to operate and predict for a human being. Especially the first order system represents well predictable dynamics without any overshoot. Extrapolation of nonlinear relations can instead be a very difficult task for humans. As a result, the desired dynamics are chosen to be linear and with an order as low as possible. Moreover, theory for linear desired dynamics is slightly simpler. Parameter scheduling can be applied for adjusting the desired dynamics. The plant dynamics are allowed to be nonlinear in all cases as it is shown in subsequent chapters.

Handling Quality Requirements

A landmark for controller optimization are the specifications stated in ADS-33 ([4]), covering important conditions for satisfying handling qualities. In general, a fast response is desired, without large overshoots and with as little time delay as possible. The controller with the fastest response however is not necessarily the best one for pilots. A predictable and reasonable fast response is preferred to an overly aggressive one. Especially an aggressive attitude disturbance rejection would lead to discomfort when hitting gusts frequently. The riding qualities as described in [5] would suffer in these cases. This issue refers e.g. to outer loops of a (rate) inner loop adaptive part or the baseline controller in case of augmentation. Additionally, large phase lags and an overly high stick sensitivity are significantly hurting handling qualities, where phase lag is a significant driver of PIOs (pilot induced oscillations).

Systemic Controller Requirements

General requirements are applicable to controllers to be certified:

1. High frequencies (compared to actuator bandwidth) in the control signal, that have virtually no effect on the plant output, are to be avoided for saving actuator wear, despite the fact that cyclic control usually needs very little energy [5].

2. Measurement noise must not lead to instability nor be significantly propagated through to the control signal.

3. Input saturation must not lead to instability or overly high performance loss apart from the missing control authority (cf. anti-wind-up architectures for integrators in PI-controllers).

4. The software may be implemented on contemporary hardware certified for aerospace. This entails limits on complexity (lines of code) as well as on numerical precision and the largest number possible to be processed. Besides, the code should be executed by a discrete solver with guaranteed numerical stiffness and precision properties.

5. A deterministic and repeatable nature of the algorithm. As opposed to unpredictable offline solvers, the controller is supposed to finish repeatedly every elementary task after $\Delta t = T$.

6. Performance guarantees during the transient response.

7. A verifiable robustness metric.

8. It should be possible to demonstrate the meaningfulness of the algorithm by formal mathematical methods.

9. Robustness against or active inclusion of input time delays.

For a certification approach, requirements for software in DO-178 (version 'C' at the time of writing) apply.
An explicit failure detection is sought to be avoided.

1.3 Chapter Overview

The motivation in Chapter 1 is followed by a list of requirements, shown in section 1.2. The compliance with the requirements is discussed in Chapter 6.
Chapter 2 provides background information about helicopter dynamics, the baseline controller, its design with the help of system identification, and an introduction to $\mathcal{L}_1$-control.
Among many alternatives, one selected combination of solutions, the *primary architecture*, is presented in the main part, Chapters 3 to 5. It is evaluated in Chapter 7, "Simulation Results".
Chapter 3 describes modules for the input channel design, covering elements for saturation and signal hedging.
Chapters 4 and 5 show the realization of $\mathcal{L}_1$-control for the controller in pitch, roll, yaw and for vertical speed, respectively.
Chapter 6 serves as set of recommendations how to tackle certification for civil aerospace.
Chapter 8 sums up the most important results and provides an outline of additional efforts that can be undertaken.

Appendix A introduces definitions and some terminology.
Appendix B refers to alternative structures of the primary method of handling decoupling of cross-couplings.
Appendix C provides a mathematical background to $\mathcal{L}_\infty$-stability.
Appendix D shows various but equivalent forms of state predictors.
Appendices E and F show the general performance and stability proofs by formal mathematics.
Appendix G provides a formal theorem for the validity of signal hedging in the predictor input channel.
Appendices H, I, J are dedicated to a robustness and sensitivity evaluation of design parameters.
Appendices K, L, M show alternative structures not being included in the primary architecture.
Appendix N shows examples of system verification.
Appendix O explains the simulation setup.

The appendix is to be understood not only as background information, but as subject matter, which, if it had been presented in the main part, would have confused the reader. However, it includes important – if not the most important – information.

1.4 Contributions of this Thesis

The thesis tries to be complete in all relevant aspects of introducing adaptive control in civil aerospace. Thus, handling qualities, signal characteristics, implementation, structural interaction, sensor noise, input channel saturations, and rigorous formal mathematics explaining the meaningfulness of the algorithms are addressed.

A modified piece-wise constant adaptive law is ported to output feedback, allowing for output feedback to perform similar to state feedback in the simulations without higher sampling rates.

Existing formal proofs of theoretical performance bounds are modified: A recursive adaptive law is included in output feedback, an initialization procedure is merged into the proof of the performance bounds of output feedback, a different strategy in the proof of the performance bounds of state feedback is shown, and some simplifications are achieved. Sensor noise is included in the formal proofs with the help of separate noise transfer functions.

The trade-off between performance and robustness is specified. It is shown that in $\mathcal{L}_1$-control the shaping of the error dynamics and the amount of modeled time delay are important elements in the trade-off, whereas the choice of the filtering structure bandwidth is largely fixed by actuators and closed-loop system bandwidth. Furthermore, it is shown that for the piece-wise constant adaptive law in scalar systems, slow error dynamics are better performing and less robust. Guidelines for the choice of the filtering structure bandwidth are presented.

The propagation of the prediction error (caused by undesired dynamics and external disturbances) to the tracking error with the role of augmentation is addressed. In this context, a new understanding of augmentation as exclusively aiding the adaptive controller in preventing disturbance propagation to the tracking error via the prediction error is suggested.

The model following nature of the $\mathcal{L}_1$-controller in comparison to the baseline controller and the robustness implications thereof are considered, while referring to adaptive and nonadaptive properties.

A simplified and an extended predictor (including the baseline controller states) are compared.

Systematic input channel design guidelines are presented. Rigorous conditions are provided for hedging signals contained in the total command vector of the input channel signal.
A special structure for a vertical speed controller is proposed. A seamless activation, robustness against mass changes, hedging of trim inputs while keeping the software implementation effort low are the most important features.
An architecture controlling the error between the desired and the real dynamics is shown.
A number of minor findings, mostly summed up in Chapter 8.1.

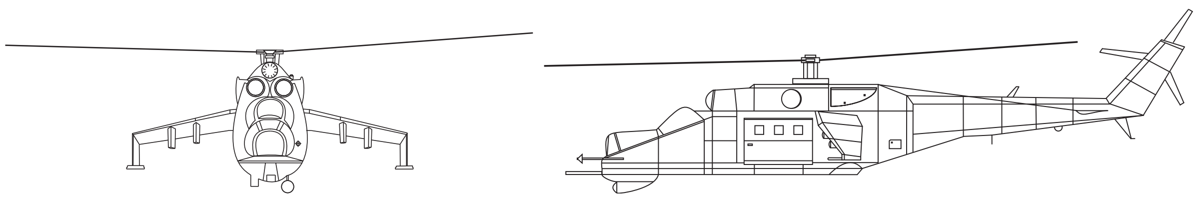
Chapter 2

Background

This chapter provides a broad outline of helicopter dynamics, the baseline controller, system identification, the concept of $\mathcal{L}_1$-control, and some other basic insights.

2.1 Helicopter Dynamics

This section introduces the reader to fundamentals of helicopter flight dynamics. A comprehensive description can be found in e.g. [5], [6], or [7] (in German language). The statements herein primarily refer to a main-tail rotor configuration depicted in Figure 2.1 (rotor blades in some trim position), but are mostly applicable to other configurations as well.



(a) Front view (b) Lateral view

FIGURE 2.1: Helicopter drawing – conventional configuration

Speaking of developing a helicopter is to a great extent equal to speaking of developing the rotor. The rotor is a system of rotor blades, spinning with approximately one constant RPM (revolutions per minute) or deliberately slightly varying RPM in modern types. The advancing blade encounters higher aerodynamic velocity in forward flight than the

retreating one. To equalize the lift in forward flight, articulated[1] blades are used, which differs from a propeller. The increase of lift in the advancing blade is compensated for by flapping, i.e. a blade movement perpendicular to the rotor plane.
A flapping hinge requires an additional lagging hinge for allowing the DOF (degree of freedom) in the rotor plane at the blade root for avoiding large moments due to flapping. Accompanied with flapping is the radius reduction of the blade CG (center of gravity), implying a velocity change due to momentum conservation. Together with the third motion, the feathering motion which is the immediate control mechanism for helicopter rotors, every blade has three degrees of freedom: flap, lag, feather. Hence, a rotor blade is a pendulum under the dominant influence of centrifugal force (gravity is small compared to centrifugal force). This structurally flexible "pendulum" experiences forces (drag, lift, hinge moments, ...) and damping (aerodynamic, structural, artificially incorporated in hinge-dampers, often in lag motion due to the smaller aerodynamic damping compared to flap). The swash plate is the element that translates commands from the non-rotating airframe to the rotating rotor. The collective input changes the AoA (angle of attack) collectively, i.e. all blades by an equal amount. The cyclic input implies with every revolution a periodic change to the AoA. With the analogy to the pendulum, a phase lag occurs from a changed AoA to the peak of the succeeding flapping motion. If there is only one central hinge (as seen in two-bladed helicopters), this phase lag is 90 *deg* for see-saw rotors and less for a hinge offset > 0 and hingeless rotors. A periodic flapping motion, where the period coincides with rotor RPM tilts the rotor plane and with it, the thrust vector. Tilting the thrust vector out of the CG, a moment is generated that tilts the airframe and with it, the rotor plane. This new thrust vector has a horizontal component (additional to trim) that causes the helicopter to accelerate in the horizontal plane. The loss in the vertical thrust component can be compensated for by a higher collective input. This is the primary mode of control, the initial change in AoA however has significant effects, too, which are most evident in hover. See also [8].

Tilting the rotor plane has effects on the fuselage and vice versa. Fuselage and rotor disc can oscillate against each other. This is more visible in roll due to the significantly lower inertia than in pitch.
With the excitation of the blade flapping mode (similar to some force on a pendulum in gravity) the signal propagation from the actuators to the actual moment on the airframe is highly dynamical. Moreover, the rotor acts as a frequency filter.
For increasing responsiveness, hingeless (sometimes even bearingless) rotors are built. The hinges are replaced with flexible structural elements which can translate moments. This has

[1]... or semi-rigid or hingeless with an elastic DOF (degree of freedom), all however with limited capability of transferring moments from the blade to the hub.

several effects: A much more responsive rotor with better (relatively stronger[2]) moment generation stands against harming stability in forward flight. A hingeless rotor is more prone to the pitch-up phenomenon.

The pitch-up phenomenon has a number of contributors: In high speed forward flight, the advancing blade encounters higher lift than the retreating one, meaning that the rotor tends to flap upwards up to 90 *deg* later, i.e. at the front of the helicopter. The more this unwanted tilt of the rotor plane and with it the thrust vector causes a nose-up moment, the higher the AoA of the advancing blade, amplifying the effect and therefore destabilizing the helicopter. Increasing rotor thrust in the collective channel causes more downwash from the rotor to hit the horizontal stabilizer and thus reducing its stabilizing effect.

The varying effects of rotor downwash to the vertical and horizontal stabilizer apply to the tail rotor as well. It serves the purpose of yaw control besides compensation for torque of the main rotor and engine. Hence, any change in the collective input is a disturbance for yaw control, alleviated by feedforward elements that increase tail rotor thrust with main rotor thrust. Being exposed to the rotor downwash and fuselage wake, the tail experiences strong disturbances due to varying flow directions and phenomenons like tail shake can be excited. Also for the tail rotor a vortex ring state exists, where vibrations, marginal controllability and loss of thrust are the consequences.

The facts mentioned so far indicate that a rotor cannot be described as a gyroscope since besides the blades' degrees of freedom flap, lag, and feathering, the rotor blades are flexible and are bent significantly. Many effects however can be observed similar to the gyroscope simply by the fact of a fast rotating mass[3]. Regressing (adverse to the rotational direction) flap or lag modes appear as nutation and precession.
These gyroscopic effects imply strong couplings on the rotor system. Other sources of cross-couplings are the above mentioned lift difference for exciting the flapping motion (advancing the flapping effect for usually 60..90 *deg*), that is the phase lag that cannot be fully compensated for by design as it is varying over flight conditions, the aerodynamic couplings of e.g. the tail, and many more effects mostly of the rotor. The swash plate is integrated only with the expected offset.

The trim attitude for a helicopter is determined by a number of influences. Some of these are the CG position, the aerodynamic velocity vector, and design traits like the vertical position of the tail rotor. With the tail rotor generating thrust in the horizontal plane,

[2]Helicopters with a see-saw rotor (central flapping hinge) often have a wide airframe as with missing moments the payload is confined to a small area in the longitudinal direction.

[3]Rotor blades are not designed to be as light as possible, but for controllability reasons heavier and for much inertia for a safer transition into autorotation.

the main rotor compensates for it. Hence, a helicopter with a CG in the geometric lateral center lands always with one side of the skids first. Besides roll, the pitch trim attitude traverses strong changes over CG position and airspeed – in hover it shows a strong nose-up attitude.

In most flight regimes, the air flow is oriented downwards through the rotor, where the rotor causes a pressure jump from the upper to the lower side of the rotor while air flow velocity remains constant. For fast descents and in case of engine failure such that thrust cannot maintain altitude any longer, the helicopter can transit into autorotation, where the flow direction is reversed, so that the air flow through the rotor keeps the rotor spinning for sufficient thrust to limit the vehicle sink rate. This state is called the wind mill brake state. The sinkrate during steady state autorotation is stable as increased drag with higher RPM slows down the rotor and less RPM increase the sink rate which again accelerates the rotor. Especially with hingeless rotors, the helicopter is still well controllable, however with changed dynamics e.g. damping and input gain.
The air flow through the rotor is sought to display a clear direction. If in slow or zero forward speed the aerodynamic velocity caused by the sink rate is close to the induced velocity of the rotor, the helicopter has entered the vortex ring state, where chaotic flows enter and leave the rotor in both directions. This state is to be avoided by the pilot as huge sink rates build up quickly and controllability suffers severely.

In conclusion, the helicopter is a very complex dynamical system due to its rotor dynamics. Multiple effects add to significant vibration levels (much higher than in most fixed-wing planes), strong interactions of aerodynamics with structure and by the lack of predictability (non-steady state aerodynamics) to an inevitable amount of unmodeled dynamics in simulations (or later predictors).
Aerodynamically, the motion of the rotor blades causes very diverse behavior over vehicle forward speed and even over one revolution. Blades work in a large range of Reynolds and Mach numbers. Local stall in the retreating blade, transonic flow in the advancing blade (e.g. buffeting)[4], high angles of attack, yawed flow, blade vortex interaction (by the blade approaching next), rotor wake interaction, and blade fuselage interaction are only a few effects to be mentioned.
In addition, structural modes become a serious issue due to the broad and intense excitation of the rotor. Controllers are equipped with notch filters to avoid excitation, especially feedback in the critical frequencies.

The heave motion in hover is controlled by the collective lever.

[4]Blade tip velocities are in hover typically at about 0.6...0.66 Ma.

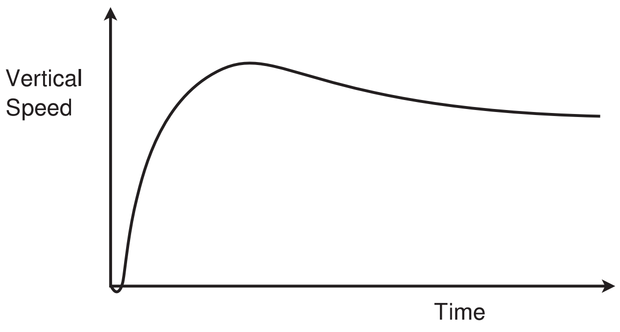


FIGURE 2.2: Qualitative natural step response of $\dot{h}(t)$ on a collective input in hover

Figure 2.2 shows a slightly simplified step response to a collective input in hover. The overshoot is explained by a higher airflow building up through the rotor which after some time decreases thrust. Naturally the response is of higher order than first or second order. The non-minimum phase characteristic undershoot arises in the time span when the new coning angle builds up.

2.2 System Description

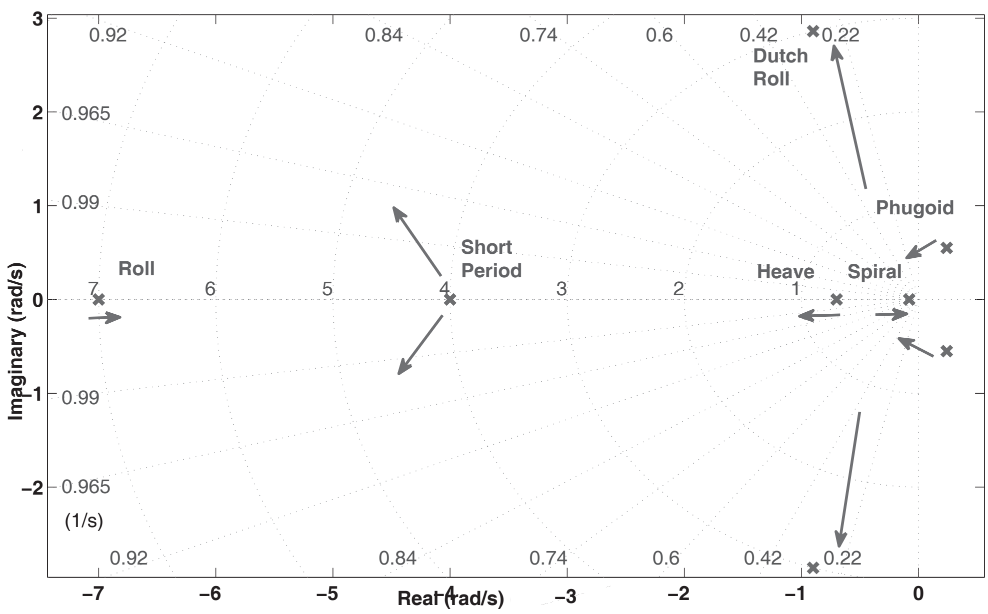


FIGURE 2.3: Exemplary helicopter eigenvalues in forward speed with their tendencies with increasing forward speed

Quantification of Helicopter Dynamics

Figure 2.3 plots open-loop eigenvalues of a fictive example helicopter, flying with moderate forward speed. The arrows point in a possible direction of pole movement when increasing forward speed of the vehicle. The eigenvalues, direction and intensity of their variation are strongly dependent on the respective helicopter design, but first and foremost on the configuration and size. The rotor design as well as position and size of the horizontal tail plane are very important factors for instance. Examples for the variation of eigenvalues over speed for the BO-105, Lynx and Puma are given in [5]. In hover for instance, the location of the eigenvalues looks very different to what is shown in Figure 2.3.

Overview of Modeling Techniques

Depending on the purpose, a helicopter can be modeled in many ways. For endurance analysis, rotational dynamics do not play an immediate role – the helicopter as point mass is sufficient. In case rotational dynamics are considered, the simplest model is a rigid body 6-DOF model. This implies the neglect of rotor dynamics. For steady state power analysis in hover and vertical flight, conservation laws combined with Bernoulli equations for fluid flow can be applied. For a more detailed analysis, blade element theory can be utilized for incorporating the rotor dynamics. Finally, rotor-fuselage interactions, dynamics of other subsystems (e.g. actuators), non-steady state aerodynamics, structural modes, and their combination to aeroelastics can be considered.

For analyzing existing dynamic objects, system identification suits. Linear state space models and equivalently transfer functions can be identified. After fixing the structure of the model by physical insight, parameters are approximated by parameter identification. Despite nonlinear dynamics, "most" of the response can be captured by low order linear models. With "most" being a weak description of accuracy, a control goal of rendering the rate response first order is considered a reasonable and feasible goal. Any response however can at best be expected with some time delay and with small non-minimum phase effects.

If a linear state space model of a helicopter for one flight condition is to be obtained, decoupling longitudinal and lateral motions provides in general unsatisfactory accuracy. The couplings are strong enough to influence other axes significantly.

Further Considerations

If only dynamics between actuator and body-fixed angular rates are considered, there is no need to adapt for unmatched uncertainties.

Apart from couplings, the inputs are not redundant, i.e. the four inputs are mapped to the four-dimensional input vector space. In good approximation, the system can be modeled input affine, i.e. the input $u(t)$ enters the system linearly. A helicopter in the conventional main- tail rotor configuration is a non-holonomic system, but controllable. Accelerations in the horizontal plane can only be achieved by attitude changes away from the trim attitude (apart from the tail rotor that induces a force in the horizontal plane).

2.3 Offline System Identification

System identification is used herein only as a tool without the ambition to modify or improve. Hence it is described marginally here, backgrounds can be found e.g. in [9].
The basic steps for offline identification are excitation of the dynamics, recording the data of input and output signals for a later offline analysis, signal processing, and analysis. A form of the Fourier transformation is used to transform the data sampled in time domain into frequency domain, e.g. the Chirp-Z transformation. Windowing techniques are applied to obtain a frequency response. If necessary, the frequency response can be used for fitting a parametric model, i.e. transfer functions or state space models. Both, a frequency response and transfer functions (or state space models) imply linear behavior and therefore have limited but often sufficient accuracy. Verification of the models can take place in time or frequency domain.
This methodology of identifying in frequency domain and the contingent fitting of parametric models is the technique used most at the time of writing.

To excite all relevant modes, a frequency sweep with exponentially increasing frequencies is applied to either the commanded angular rate or the commanded attitude. Figure 2.4 shows a typical frequency sweep. If applied to rate commands, a short signal in the rate command (as shown in Fig. 2.4) for a small attitude change is added to the initiated sweep in order to shift the response to be around a trim attitude. The integrated sine wave of the rate would otherwise result in the attitude to be exclusively above or below the initial trim attitude. For a constant amplitude of the attitude, the amplitude of the rate is growing with the frequency as factor.

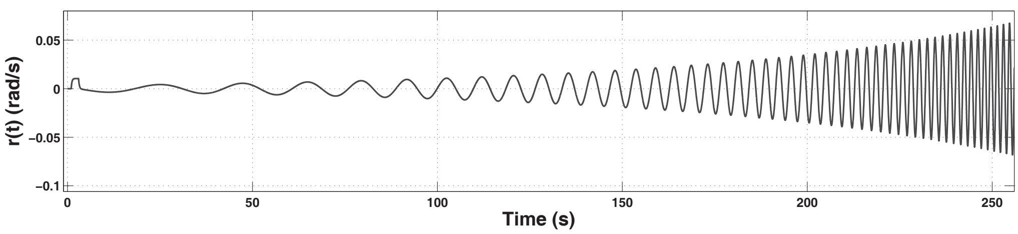


FIGURE 2.4: Exemplary frequency sweep applied to the rate command

Identification of rotorcrafts is challenging due to the high vibration level, highly coupled dynamics, unstable modes, etc..

It is recommended to adhere to the following:

- Data collection with a deactivated (baseline) controller is desirable to avoid correlations. A weakened controller is also often possible; weak gains however may have adverse effects due to rotor dynamics, the lead-lag eigenmode in particular.
- Identified correlations due to couplings can be mitigated by applying MIMO-identification techniques.
- If on the axis to be identified a computer generated frequency sweep (sinusoidal signal with exponentially increasing frequency) is applied to the input, a good method to eschew correlations from the other axes is to stabilize it manually with uncorrelated inputs. The frequency content for stabilizing off-axes should be decoupled from the on-axis.
- If achievable closed-loop desired dynamics are to be identified, the baseline controller is active and defines the assumingly decoupled closed-loop dynamics. SISO identification in both cases is justified.
- Despite the nonlinear behavior of helicopters (it may be approximated linearly very well), only linear identification is applied. Identification of nonlinearities can easily introduce more distortion than improvements due to its complexity.
- To capture basic dynamics, transfer functions of low order (e.g. 2...5) can be sufficient for e.g. implementing the identified transfer function as predictor dynamics (= desired dynamics in $\mathcal{L}_1$-control) for augmentation. The lowest acceptable order dependent on the identified axis and on the helicopter type is aimed at.
- Contingent on the required accuracy of the identification, it is conducted at several points of the flight envelope. Most often, indicated airspeed is chosen as parameter to vary.
- When fitted to a frequency response, the structure of the parametric model is to be physically reasonable. It is desirable that also parameters obtained by the optimizer are physically meaningful, e.g. the roll time constant is usually approximately known and is expected to capture most of the roll dynamics.