Using Ferraris sensors for drive optimization

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Speed-controlled drives are subject to ever increasing demands with regard to dynamics, smooth running and disturbance resistance. To achieve this, vibration must be reduced as far as possible - also to prevent wear or undesirable side-effects such as the generation of noise and heat. Relative acceleration sensors on the Ferraris principle perform sterling service when it is necessary to analyze drive systems in order to improve the quality of the system as a whole. Furthermore, if the sensors are incorporated into the control loop, then the control-loop performance can be considerably improved.

The acceleration is indispensable as a state-variable for precise analysis of the dynamic response of a drive system. This is because it represents the direct, undelayed response of a mass being moved in reaction to all the forces acting on it. If one assumes that in the typical drive control loop there is usually a position sensor implemented to detect the actual value, then it would – theoretically – be possible to calculate the acceleration by double-differentiation of the position signal. In practice, the signal derived in this way would be useless, since each differentiation exaggerates any errors present, and so a double differentiation would inevitably produce a very noisy signal. The situation is even more critical for *highly dynamic* systems. In this case, even a directly produced *velocity* signal, such as the output signal from a tachogenerator, is not suitable for the generation of a good acceleration signal – even the short sampling time that is required by the control system for a single differentiation will lead to sizeable quantization errors – quite apart from the amplification of any errors. In other words, for the analysis of highly dynamic systems, the acceleration must be measured *directly*.

Classic acceleration sensors on the spring-mass principle have inherent disadvantages. They measure the *absolute* acceleration not the *relative* acceleration, which may be relevant. For example, consider a handling robot, with the hand axis mounted on a rotary axis, and where it is necessary to sense the dynamics of the hand movement *relative* to the higher-level rotary axis. Furthermore, a spring-mass system is frequently sensitive to motion orthogonal to the measurement axis, so that the required measurement may be falsified.

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This effect can arise, for instance, on a machine-tool compound slide, where the top slide is moving in the X direction, while the cross slide is simultaneously moving in the Y direction. And where *rotary* movements are concerned, the application of absolute acceleration sensors is extremely complicated. The energy supply and signal transmission requires the use of slip-rings or contactless forms of transmission, such as rotary transformers or telemetry systems.

Functional principle of the Ferraris sensor

Considerable improvements in the analysis of drive systems can be achieved by using relative acceleration sensors based on the *Ferraris* principle, named after the Italian Galileo Ferraris [1]. The principle is that permanent magnets mounted in a fixed detector unit induce eddy currents in a moving, conductive, but non-magnetic material. For measuring rotary acceleration this material can be in the form of a disk, for linear acceleration it is formed as a strip of metal (see **title picture**). The eddy currents and the magnetic fields that they generate are proportional to the radial velocity of the disk (or the linear velocity of the strip). A change in the eddy current produces a voltage in the coils mounted in the detector unit that is proportional to the rate of change of the velocity, i.e. proportional to the acceleration. The reverse application of this principle has, incidentally, been used for a very long time in electricity consumption meters. The decisive factor is that the differentiation is not based on a sample over a discrete time period, but is a physical effect, so that the user sees a dynamic, low-noise acceleration signal.

Patented arrangement of permanent magnets and detector coils

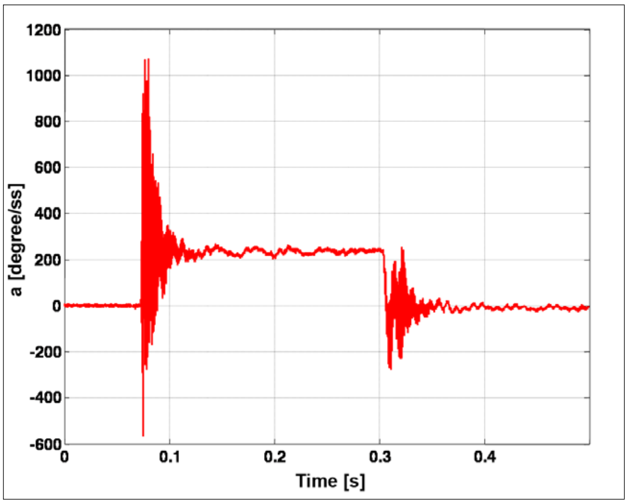
Even though this procedure may seem quite straightforward, a considerable development effort was necessary in order to optimize the sensor and make it suitable for practical use. For instance, only a special, patented arrangement of *several* permanent magnets and detector coils ensures that electromagnetic fields, which are particularly prevalent in electrical drives, do not affect the measurement signal. The final aim is always to obtain the most advantageous results from the Ferraris sensor for the particular application, while simultaneously achieving a maximum reduction of undesired side-effects – such as the "eddy current braking" of the sensor – in designs that often have a customer-specific adaptation.

Ferraris sensors for analyzing systems

The Ferraris sensor has already established a firm niche for itself, particularly for all types of test-bed, where it is used for the following tasks:

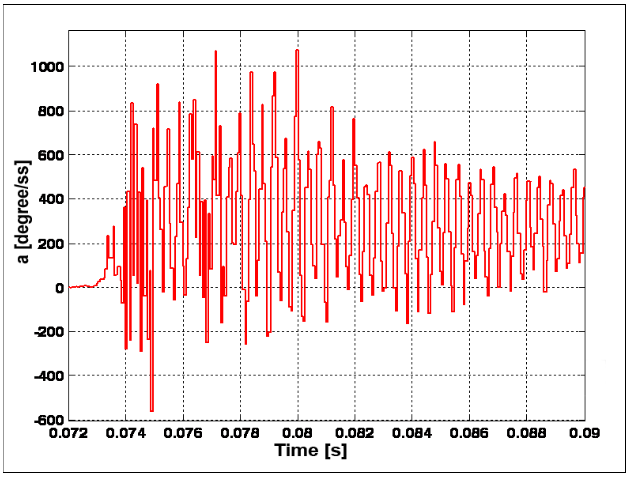
- vibration analysis
- smooth-running test
- identification of mechanical parameters (mass, moment of inertia, damping)
- reconstruction of force, torque and friction
- detection of the causes of unwanted noise
- monitoring motors and bearings
- measuring frequency response.

The example in **Fig. 1 a** shows how a Ferraris sensor reveals torsional vibrations in a drive chain that are stimulated by the application of increasing torque. **Fig. 1 b** shows the initial transient as an extract at a higher resolution. As a comparison, **Fig. 1 c** shows – for the same section – how limited the analytical options would be if only the position information was available, even if the sensor was a *high-resolution* incremental sine encoder ("reference encoder") that can acquire the position with a resolution of 70 micro-degrees. Even the very short sampling time that is required (25 µs) for differentiation leads to a *velocity signal* (green line) with such a strong quantization that it can no longer be usefully evaluated. In this case, measurement of the torsional vibration (at about 2500 Hz) is only feasible with the Ferraris sensor. If one proceeds in the other direction, i.e. by integrating the acceleration signal from Fig. 1 b, the result is an excellent, low-quantization velocity signal (the red line in Fig. 1 c). This plays a role if (as will be explained later) the



1 a

Measuring the torsional vibration of a drive chain, see text for explanation



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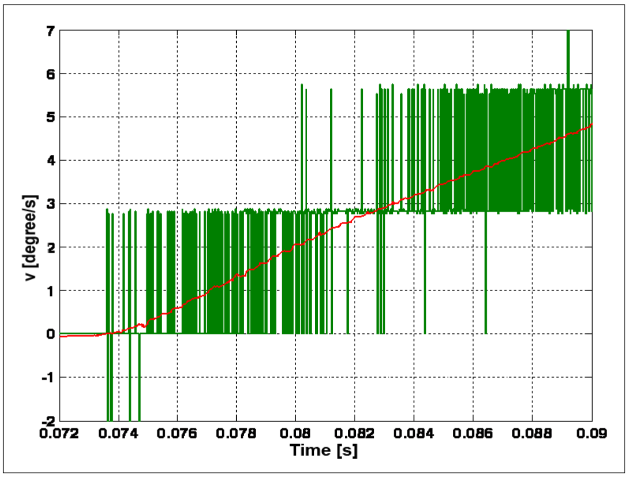

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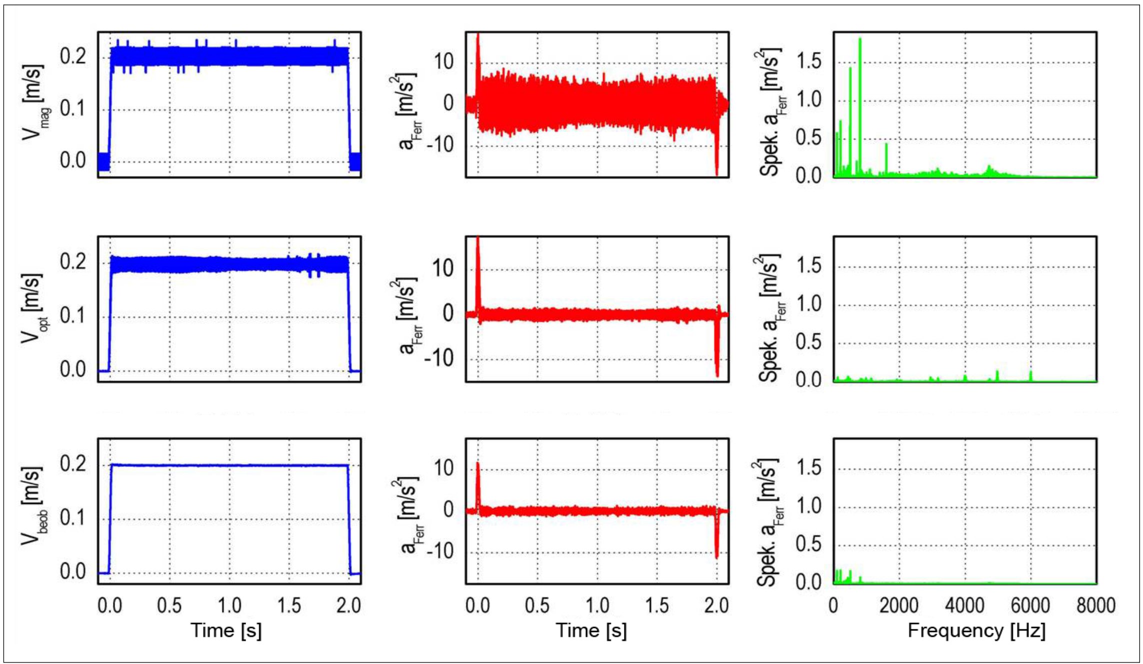

2: Control loop dynamics using various sensors, see text for explanation

Ferraris sensor is to be used not just for analytical purposes, but also to improve the control-loop performance. By the way, for the type ACC 70 used here, the eddy current material is formed not as a disk, but as a cylinder ("eddy current bell") and mounted on the shaft with the help of a clamp.

Advantageous over existing systems for analysis

Often it is the Ferraris technology that makes extended analysis possible at all. For instance, investigations of the noise behavior of vehicle gearboxes have shown that conventional methods, such as the measurement of sound in air and solid materials, is as vital as ever for judging the acoustic situations. But *precise* information on the *causes* of the airborne and conducted sound only became possible when Ferraris sensors were used. Even a few measurements made it possible to narrow down the origins of the noise [2]. And sometimes fitting problems, or just plain costs, are the reason for preferring the Ferraris sensing technique over existing technologies.

Combining Ferraris sensors with position encoders for better control-loop performance

As already mentioned above, the possible applications for Ferraris sensors go far beyond the pure *analysis* of systems. Let us recall that a classic P-PI drive controller always needs the momentary speed available as a state variable, regardless of whether the speed or the position is the variable that is to be controlled. If, in this case, one uses not only the position signal from the position encoder in the control loop, but *also* the integrated signal from a Ferraris sensor as the velocity signal (instead of deriving it from the position signal), then the dynamics, disturbance resistance and smoothness of the drive will be significantly improved. In this way, the Ferraris sensor becomes part of the control loop, and the resulting quietness of the system also reduces the wear on mechanical components, prevents the generation of unwanted noise, and reduces the power loss in the motor.

Advantages of Ferraris acceleration sensors at a glance:

1. relative, contactless, active measurement principle
2. high linearity and sensitivity
3. no lower frequency limit, high bandwidth possible
4. very low noise, inherently zero offset voltage
5. no sensitivity orthogonal to measurement direction
6. compact dimensions
7. easy mounting and adaptation to existing fittings
8. large permissible mounting tolerance
9. mechanically rigid construction, no coupling required
10. no movable parts in the sensor head
11. insensitive to dirt
12. very robust, resistant to extreme shock loading

Usable even in tough environmental conditions

The example in **Fig. 2** shows the dynamic response of a drive with a P-PI control loop when various sensors are used. The first (top line) is the acquisition of the momentary values by a magnetic incremental measurement system with a low resolution. The spectrum measured with the help of the Ferraris sensor shows that there are clear indications of stimulated vibration caused by errors in the velocity signal. As is to be expected, a better control-loop perfromance is achieved if an optical measurement system is used that has a higher resolution (middle line). Nevertheless, stimulated oscillation can still be detected, which results from interpolation errors and can be heard as definite sounds (a high-frequency "chirping"). If the Ferraris sensor is now used not just as a pure measuring device, but also integrated into the control loop (in combination with the magnetic measurement system), then these stimulated oscillations are largely eliminated (lower line in Fig. 2).

The combination goes beyond the possibilities of optical encoders

The *combination* of a *low* resolution magnetic measurement system with a Ferraris sensor in fact produces significantly better results for the control loop performance than the use of a *high* resolution optical position sensor by itself. Putting it another way: the *combination* of a magnetic measurement system and a Ferraris sensor provides the controller with a sum of information that, in effect, matches that produced by a very high resolution optical system. This is especially interesting for applications where the use of an optical encoder is excluded right from the start, for reasons of cost or robustness. Another advantage of this combination is that it is considerably less restricted with regard to speed or traversing velocity than an *optical* measurement system with a comparable resolution, which would have to be fitted with a sealed protective enclosure to achieve a similar degree of robustness.

Wiederstein et al. [3] describe the integration of a Ferraris sensor in the control loop of a direct drive for a printing press. This was based on preceding comprehensive investigations, in the course of which it became apparent that it would not be possible, without considerable effort, to achieve improved control-loop characteristics for a drive which had already been laid out for high-performance. But the Ferraris sensor allowed considerable improvement in both the command characteristic and the disturbance reaction. Active stabilization of the drive resonance was achieved, and non-linear effects also become more controllable. In particular, torque jolts on the load side were easier to counteract with the aid of a Ferraris sensor than with previous methods. Since the disturbance response plays an important, possibly decisive role, not only in printing presses but also in other applications, such as machine tools, the authors conclude that these results are of significance over a far wider area than the specific application that was investigated.

Present developments at Baumer Hübner are concerned with the optimization of the combination of Ferraris sensors and position measurement systems with respect to both the mechanical design and the signal electronics, so that the user is able to take full advantage of the Ferraris technology to improve the control loop performance, without having to make adaptations to the classic control loop structure.

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