8

Mating systems

The objective of this chapter is to provide a basic understanding of the dynamic and kinematic processes which are taking place during docking or berthing of two vehicles, and to give an overview of the design principles used for docking and berthing mechanisms. Design driving requirements for these mechanisms are briefly discussed, and an overview of existing mechanism developments is given. The dynamic processes of contact and capture at docking are discussed using a simple model of an equivalent mass, which represents the masses of both spacecraft plus a central attenuation system. Basic functional concepts of the design elements used for shock attenuation, capture, structural connection and sealing are discussed at the end of the chapter.

8.1 Basic concepts of docking and berthing

The main tasks and issues arising during docking and berthing have already been addressed in section 2.5. Definitions of the terms 'docking' and 'berthing' have been given in chapter 1. For completeness of this chapter, these key definitions shall be recalled here.

- As a general term for the process of achieving contact, capture and connection, the term *mating* is used. This includes the two cases 'docking' and 'berthing'.
- The term *docking* is used for the case where the GNC system of the chaser controls the required vehicle state parameters necessary to ensure that its capture interfaces enter into those of the target vehicle, and where the capture location is also the location for structural connection.
- The term *berthing* is used for the case, where
  - the GNC system of the chaser delivers the vehicle to a meeting point with zero nominal relative velocities and angular rates;

– a manipulator, located on either target or chaser vehicle, grapples the corresponding capture interface on the other vehicle;
– the manipulator transfers the captured vehicle with its attachment interface to the final position at the relevant target berthing port and inserts it into the corresponding attachment interfaces of the target vehicle.

As already shown in figure 2.13, for docking, the capture and attachment interfaces are integrated into a single system, the main axis of which is the approach axis. In berthing, the approach axis and the axis of attachment, and hence the interfaces for capture and attachment, are fully de-coupled. The transfer from the capture position to the attachment position by a manipulator makes it possible to access different berthing ports, as shown in figure 5.4.

In order to give an overview of the functions and operations involved in the processes of mating of two spacecraft, and to recall the major constraints and interface requirements (some of them have been addressed already in previous chapters), the sequence of operations of a typical docking process and of a typical berthing process are described in the following sections.

8.1.1 Docking operations

Depending on the type of mission, unpressurised (usually for completely unmanned mission scenarios) or pressurised (for missions including astronauts in one or both vehicles) docking mechanisms will be used (see section 8.2). The following description of a typical docking process is based on a manned scenario, which involves the more complex functions, as an air-tight transfer passage has to be established.

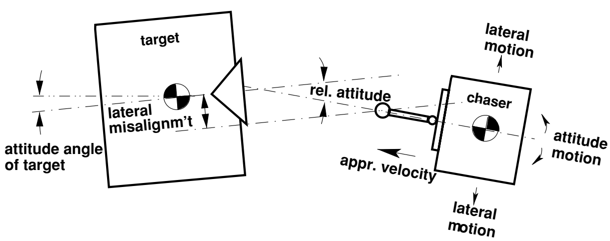

Figure 8.1. Alignment and motion parameters at docking contact.

(1) *Reduction of approach velocity and misalignments.* During and/or after acquisition of the docking axis, the chaser reduces its approach velocity to the final value. The last part of the approach down to contact will be flown with constant velocity, avoiding braking thrusts in the last few metres and plume impingement on the target at close distance. During the last few metres of approach the chaser GNC must achieve the lateral and angular alignment which is necessary to place docking interfaces of chaser and target into each other's reception range.

(2) *Reception*. In this phase, the docking interfaces of the two vehicles enter into each other's reception range. This is the range within which physical contact between the two vehicles occurs and capture of the according interfaces is possible. The reception range must be large enough to cover all residual dispersions of the chaser w.r.t. the target vehicle. The reception range must also cover all rebound motion, which may take place after first contact prior to completion of capture.

(3) *Impact attenuation*. If the interface structures impact on each other without shock absorbers, they would rebound, with the deceleration and re-acceleration dependent on the elastic and plastic deformations of the contacting structures and of their sub-structure. As the change of velocity would happen over a short distance, the accelerations would be high and the rebound would take place within a short time. For this reason, spring-damper devices have to be applied; these reduce the relative velocity (the velocity change occurs over a longer distance) to

- reduce the shock of impact on the structures of the two vehicles;
- make the alignment of the capture interfaces possible;
- decrease the rebound velocity; and
- increase the time available for the capture process.

(4) *Capture*. After entering into their reception ranges, the capture interface structures of both sides can guide each other (because of the compliance of the attenuation system) into the conditions of alignment, at which capture can be completed. The term 'capture' simply means that the vehicles can no longer escape from each other. It does not imply, however, that a rigid connection has been established. Operation of the capture latches can be achieved, e.g., by springs and by the kinetic energy available from the residual velocity between chaser and target; this is comparable to a spring-loaded door-latch falling into its catch. Otherwise, operation of capture latches can be initiated by sensors and actuated by electric motors. Such sensors could be contact or force sensors, or sensors observing the entry of interfaces into the capture range.

(5) *Retraction and structural alignment*. After capture, the two spacecraft are still only relatively loosely connected to each other, and the residual distance and the lateral and angular misalignments in general will not allow immediate engagement of the structural latches. On the contrary, in most designs, the springs of the shock attenuator system will push the two bodies away from each other up to the limits given by the capture latches. For this reason, in most designs a retraction mechanism will be necessary to pull the docking interface planes of the two craft together. This generally includes additional mechanical guiding features (e.g. pin–cone, ball–groove), ensuring improved alignment during the retraction motion, as is necessary for structural connection.

(6) *Structural connection*. Once they are properly aligned, the structural latches can be engaged. They will press the two interface planes together under a pre-load, which ensures a stiff structural connection under all load conditions which potentially could occur during operation as a combined spacecraft. In the case of pressurised docking ports, the structural latches also have to apply the compression forces for the sealing rings, which are required to achieve a gas-tight connection. In some docking mechanism designs, one or more of the functions of capture latch, attenuation system, retraction mechanism and structural latch can be combined.

(7) *Utilities connection*. After proper structural latching, utility connections can be engaged. This will be possible at this point in time only if connections are performed automatically. Otherwise, utility connections may be performed by the crew after pressurisation and hatch opening. In many cases, only electrical connections for power and data will be required. In some mission scenarios there are, however, also fluid and gas connections, e.g. for re-supply of propellant, water and/or air to the target spacecraft. After connection of the data lines, the systems of the chaser spacecraft can be directly monitored and, where necessary, commanded by the target.

(8) *Pressurisation*. In the case of pressurised docking ports, after successful structural latching, the pressurisation of the volume between the hatches can commence. Information provided by pressure sensors in the tunnel and between two concentric sealing rings will be monitored during pressurisation to verify gas tightness.

(9) *Opening of hatches*. When pressurisation has been established and gas tightness has been verified, the hatches can be opened and the post-docking operations according to the mission objectives can begin.

8.1.2 Berthing operations

In principle, the manipulator arm can be mounted either on the target or on the chaser vehicle, and correspondingly the grapple fixture should be mounted on the opposite vehicle (see figure 2.13).

In the following description, which is based on the ISS scenario, it is assumed that the manipulator is located on the target vehicle.

(1) *Acquisition of berthing box by chaser*. At the end of the approach, the chaser vehicle will perform station keeping in a berthing box, as described in sections 5.3.1 and 5.7.2. The berthing box is a volume located very close to the target station into which the chaser has to be placed, to make capture of the grapple interfaces by the manipulator arm possible.

(2) *Acquisition of readiness position by manipulator*. Once the chaser is in the berthing box, the manipulator front end with its end-effector will be moved to a position

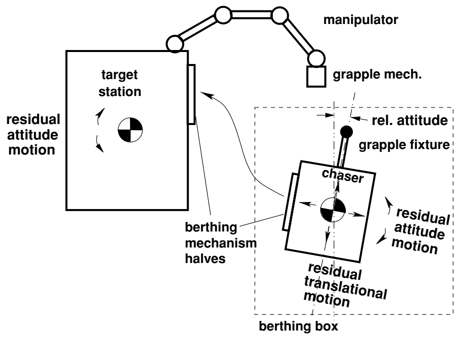

Figure 8.2. Berthing scenario: conditions at capture.

from where capture operations can start. As a rule, for safety reasons, the manipulator will not be in this position during acquisition of the berthing box by the chaser.

(3) *Switch-off of chaser thrusters and initiation of capture*. When the front end of the manipulator has acquired the readiness position and when it has been verified that the grapple fixture is within the 'inner berthing box' (see figure 5.6), the propulsion system of the chaser will be inhibited and the manipulator will be steered to pursue with its end-effector the grapple fixture on the chaser. After thrust inhibition, the chaser will start to move away due to the effects of orbital dynamics (see figure 5.5). As a result of this motion, capture has to be performed within a limited time, typically 1 or 2 minutes, depending on the position of the berthing box w.r.t. the target orbit (V-bar).

(4) *Grappling of capture interfaces by manipulator.* When the correct position of the capture tool (end-effector) is achieved, the grappling operation is initiated. Similar to the docking operation, grappling has to ensure that the interfaces can no longer escape each other, and subsequently that the connection between the manipulator and the captured vehicle is sufficiently rigid to comply with the needs for transfer and insertion.

Correct position of the capture tool w.r.t. the capture interface on the other vehicle (grapple fixture) requires a sensing function; this has to provide the same type of information as required for docking, i.e. range, LOS angles and relative attitude angles. At the time of writing, this sensor function has been fulfilled in all berthing missions by a human operator with the aid of a camera, mounted on the end-effector, and a target pattern near to the grapple fixture, similar to the one shown in figure 6.25. In future manipulator operations for berthing, this function may also be performed automatically.

(5) *Transfer to the berthing port.* The front end of the manipulator will be steered so as to perform all necessary translations and rotations to move the berthing mechanism interfaces of the captured vehicle to those of the target berthing port on the station. As the captured vehicle will in most cases obscure the vision of the manipulator camera used for capture (wrist camera of manipulator), different sensing functions are necessary for transfer. As the accuracy requirements for steering of the manipulator arm during transfer are moderate, the internal angular sensors of the manipulator joints may be generally sufficient. A path plan will be used which ensures that, during transfer, no collision between the body to be berthed and the structure of the station will occur.

(6) *Insertion into reception interfaces*. As for docking mechanisms, berthing mechanisms also have a reception range which must be measured according to the positioning accuracy of the manipulator. A sensing function is required to verify proper positioning of the berthing interfaces w.r.t. each other. If the joint angle sensors of the manipulator cannot provide sufficient accuracy, additional sensing devices (e.g. camera and visual target pattern) may have to be provided.

    After proper positioning has been established, the manipulator will push the berthing interfaces of the captured vehicle gently into those on the berthing port of the station. Alignment will be achieved by the manipulator forces and guiding features (i.e. first by alignment petals and eventually by pin–cone or ball–groove combinations). The manipulator can provide these pushing forces until structural connection commences. In contrast to docking, insertion into the berthing interfaces can be a very slow process, as this is fully controlled by the manipulator.

(7) *Structural connection, utilities connection, pressurisation and hatch opening*. These operational steps and functions are in principle no different than the ones for docking, and therefore need not be repeated here.

Berthing techniques can be used also for other applications, e.g. the transfer of modules or other structural components from one location to another. Examples are the transfer of Mir modules from docking location to the final location, or the unloading and attachment to the ISS by manipulator arms of cargo items from the cargo bay of the Space Shuttle Orbiter. The transfer of the modules of the Mir Space Station from one fixed position to another one has been performed automatically without active control by a human operator.

8.1.3 Commonalities and major differences between docking and berthing

The above descriptions of operational sequences show that for both docking and berthing the same basic types of operations are required:

- acquisition of capture reception range;

- closure of capture devices;
- transfer to and alignment with operating range of structural latches;
- closure of structural latches;
- pressurisation of tunnel (mission dependent);
- hatch opening (mission dependent).

For *docking*, the functions for capture and attachment are concentrated at one location on each vehicle and integrated into one system, the active half of which, in the majority of cases, is on the chaser side. The acquisition of the capture range is performed by the GNC system of the chaser. Capture is initiated automatically either by passive spring-loaded latches falling into their corresponding catches on the other vehicle, or by active latches initiated by sensor signals. Due to the integration of capture and transfer functions, the transfer from the capture position to the attachment position is very short. It is typically performed by a simple retraction of the front end of the mechanism to the base structure.

For *berthing*, the functions for capture and attachment are at different locations on both vehicles. Capture is performed actively by a tool which is able to pursue and capture the according interface on the other vehicle in a much wider range of positions and attitudes than for docking. From the capture position, the captured body can be transferred to a wide range of potential attachment locations. As a result, in contrast to docking, this transfer has to be performed via a long and complex path. The price to be paid for the additional flexibility concerning capture location and attachment location is the much increased complexity in terms of tools and operations required for capture and transfer. The tools required are a large manipulator arm and an end-effector. The increased operational complexity is due to:

(a) the dynamic interactions between three systems, i.e. the approaching vehicle controlled by its GNC system, the body dynamics of the target station, with or without active GNC, and the manipulator system;

(b) the inherently more complex capture and transfer operations by a manipulator, which is actively controlled by the human operator in the loop.

For docking, the GNC performance parameters (i.e. velocity in approach direction, lateral and angular alignment and rates) will determine the size of the reception range and the size of the spring-damper equipment. Different design principles can be used for these functions, depending on whether the docking contact will be at high or very low speed. Generally, the better the GNC performance, the lower the approach velocity at contact can be.

In the case of capture for berthing, the absolute alignment of the chaser vehicle plays, compared with the residual rates, a secondary role, as already discussed in sections

5.3.1 and 7.1.1. In order to stay in a berthing box of, e.g., 1 m^3 for 1 minute, residual velocities in all directions must not be higher than 0.01 m/s. Residual angular rates must be compatible with the tracking capabilities of the manipulator and the human operator. Considering an initial misalignment of, e.g., 10 deg and a residual rate of 0.1 deg/s, the final misalignment after 1 minute would be 16 deg. This type of rate and misalignment could still be handled by a manipulator.

For completeness, the general advantages and disadvantages of docking and berthing shall be recalled here.

Docking operations are generally less complex, more reliable and less time consuming than berthing operations. Docking mechanisms generally require, however, larger reception and damping devices than berthing mechanisms. Capture has to be achieved in a few seconds after contact, otherwise the vehicles will move away from each other. Because of the angular motion (potentially induced by the contact of the vehicles), a failed capture is more safety-critical in docking than in berthing.

Berthing allows attachment to locations on the target vehicle which would be inaccessible for docking. As capture takes place at nominally zero relative velocity between the two vehicles, impact shocks and forces will be small. This requires, however, that the GNC of the chaser is capable of leaving the vehicle in the volume of the berthing box at very low residual velocities and angular rates after thrust inhibit. The time available for capture depends on the residual velocities, on the capture location w.r.t. V-bar, on the constraints imposed by the target vehicle geometry and on the capabilities of the manipulator. The capture window available after control inhibit of the chaser is typically of the order of 1 to 2 minutes. Failure of capture within this time leaves the chaser vehicle in a safe state w.r.t. collision with the target structure, if the rules of the berthing box definition (see section 5.3.1) have been followed. The necessity of a large manipulator is a penalty, in principle, in terms of mass to be launched and investment cost. These considerations may, however, play a secondary role for the mission design of the chaser, e.g. if such a manipulator is available on the target station anyway. The time required for capture, transfer and attachment to the berthing port is, in any case, a penalty concerning mission resources, in particular concerning crew time.

8.2 Types of docking and berthing mechanisms

In this section the characteristics of the different types of mechanisms for attachment will be discussed in general terms. The discussion looks, in particular, at the mutual dependence of the design driving functions. These are the capture function and the functions involved in the establishment of a passage for transfer of goods between the vehicles. The latter functions include the structural connection and, in the manned scenario, the seals and hatches required to establish a pressurised tunnel between the spacecraft. Examples are given of previously developed different types of mechanisms, and actual implementations of these features are shown. A very detailed description of central and peripheral docking mechanisms for manned spacecraft, together with a comprehensive discussion of the major design elements of the Russian systems, can be found in (Syromiatnikov 1990). An overview of docking and berthing interfaces and of docking/berthing requirements and parameters, together with an extensive list of reference documents, is given in (AIAA 1993).

8.2.1 Design driving requirements

The design and size of mating mechanisms are determined by a number of factors, which depend on the mission objectives and the dynamic conditions at contact of the chaser and target halves of the mechanism.

Transfer of crew and goods

Unmanned missions In unmanned missions, i.e. where neither spacecraft is designed to be habitable, there is generally no need for a pressurised transfer tunnel. For this reason, the design of unpressurised docking and berthing mechanisms will typically be determined by requirements for load carrying capability, stiffness and, in some cases, alignment accuracy. Unpressurised mating mechanisms are much simpler in design, as no air-tight connection has to be established.

Manned missions In manned missions, at least one of the two spacecraft is permanently or intermittently manned; usually this is the orbiting target station. This requires transfer of goods to the pressurised areas of the station, and for this reason also a supply vehicle usually has a pressurised area so items may be used inside the station. For the transfer, a tunnel has to be formed after mating, which provides a pressurised passage. The diameter of the docking or berthing mechanism is mainly dependent on the size of the tunnel required for transfer of crew and goods. As a rule, the minimum cross section of hatch and tunnel should allow the passage of an astronaut in his space suit.

Contact parameters

The necessary reception range is mainly determined by the lateral and angular misalignments between the two halves of the attachment mechanism at insertion. The design and size of the attenuation devices are determined by the relative translational velocities and angular rates at contact. In the case of docking mechanisms, these are the approach velocity, lateral velocities and angular rates, determined by the GNC performance of the chaser. In berthing mechanisms, these values are determined by the performance of the manipulator and the sensors used to guide it. There are two occasions of capture which have to be considered in the case of berthing: capture of the grapple fixture, and capture after insertion of the berthing interfaces of the captured vehicle into those of the target station. As insertion velocities by a manipulator can be very low, for berthing there will be no need for large shock attenuation systems, and there will also be no driving constraints for the closure time of latches.

Requirements for utility transfer

Utility lines for, e.g., power, data, fluids, gas, require a certain area on the docking or berthing interface plane for connectors or line feed-throughs. Utility connections can be performed either automatically or, in the case of pressurised attachment interfaces, by hand. If performed automatically, additional areas for the connection mechanism must be provided. In pressurised mating mechanisms, such areas must be outside the minimum diameter required for the transfer of crew and goods. If performed by hand, the connections need to be inside the tunnel, whereas automatic connectors can be located either inside or outside. The latter location may be chosen, e.g., for safety reasons in case of fluid connectors for toxic propellants.

The sizing requirements for a pressurised mating mechanism are shown in figure 8.3. The design driving feature, shown here for the inner cross section, is a space-suited astronaut. There can, however, be other requirements, e.g. the transfer of standard racks, which are bigger than a space suit. This was the design driving feature, e.g., in the berthing mechanism for the ISS. A discussion of sizing requirements for docking/berthing systems can be found in Tobias,Venditti & Cable (1989).

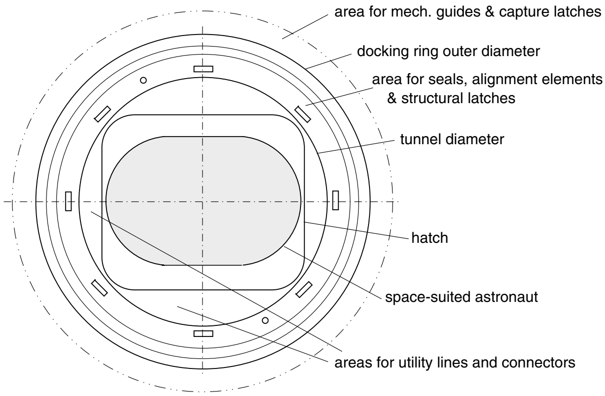

Figure 8.3. Sizing features for pressurised mating mechanisms.

The diameter of the pressurised tunnel eventually becomes a design driver for the choice of structural connection latches, as the latch forces will increase with the square of the tunnel diameter. The repercussions of this effect on the design of docking ring structure, seals and latches are discussed in more detail in section 8.3.6.

Mating devices which perfectly fit the needs of a particular mission can, in general, be designed only if both the chaser and the target are developed at the same time. In servicing missions, the target spacecraft will usually have been in orbit for a long time, and therefore the mating devices of the chaser will have to fit the interfaces available on the target. This is true in particular for a supply vehicle visiting a space station.

These interfaces are usually conceived and designed early in the development phase, or their design may even be taken from those used in former missions, and the operational phase in orbit may last one or two decades. In principle, for the operational lifetime of the station, visiting vehicles will have to comply with these interfaces. As a result, newly designed supply vehicles may have to use mating devices, the design of which may be very old and not fully optimised for the mission. Only in cases where later structural items are added to the station will there be a chance to add a new design for the mating devices.

8.2.2 Central vs. peripheral docking mechanisms

For docking mechanisms, the requirement for effective alignment for capture at the first contact can most easily be implemented by a central capture mechanism. This will consist (on the side of the active vehicle) of a rod (also called a probe) with one end flexibly connected to the spacecraft structure, and (on the side of the passive vehicle) of a hollow cone (also called a drogue) receiving the tip of the rod and guiding it to the cone centre, where it can be captured. This process is described in more detail in section 8.3. All early docking mechanism designs used in the American and Russian space programmes were based on this principle (Bloom and Campbell 1970; Syromiatnikov 1971; Syromiatnikov 1990). The disadvantage of a central docking mechanism is that, after successful attachment and hatch opening, the capture mechanism components, i.e. the rod mechanism on the active side and the capture cone on the passive side, are in the way of the transfer tunnel (see figure 8.4). They have to be removed and stored elsewhere before transfer of crew and goods can take place.

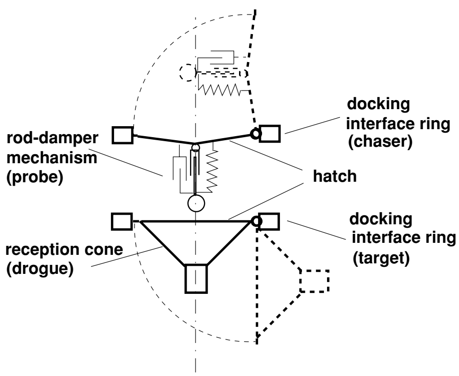

Figure 8.4. Central docking mechanism: obstacles after hatch opening.

To avoid this disadvantage, designers have looked into the possibilities of arranging the functional elements necessary for reception, mechanical guidance and capture at the periphery of the interface rings establishing the transfer tunnel (Syromiatnikov 1971, 1990). Most of the area inside the interface ring is then free for the passage, as only a flat hatch has to be opened, as shown in figure 8.5. Reception and capture principles, such as the V-latch for unpressurised attachment (see figure 8.6), could be arranged in principle around the interface ring. Peripheral attachment systems also provide the possibility for an androgynous design. Whereas a central system will always have a male and a female side, a peripheral system can be arranged such that reception, guidance and capture functions are available on both sides. Such systems are called 'androgynous' (see also the next section) and have reception and guidance elements formed like the petals of a flower arranged around the docking ring. They were used for the first time in the Apollo–Soyuz docking project in 1975 (Swan 1976; Syromiatnikov 1990); figure 8.9. This basic design has been followed by practically all peripheral mating mechanism developments thereafter, and is presently used in the design of the APDS (Androgynous Peripheral Docking System, figure 8.10; Syromitnikov 1990), originally designed for the Russian space programme and now used for the docking of the US Space Shuttle with the ISS, and by the CBS (Common Berthing Mechanism, figure 8.13; Illi 1992), the attachment mechanism for the pressurised modules on the 'US' side of the ISS.

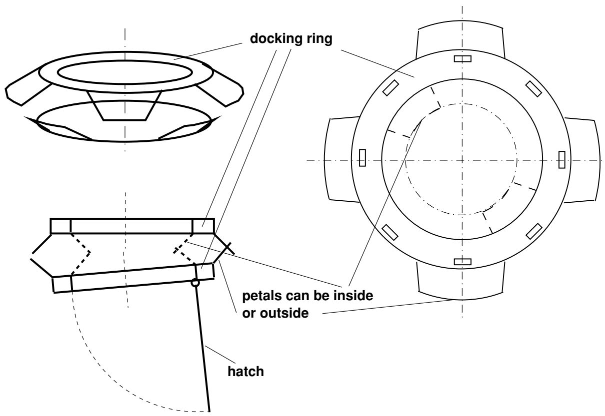

Figure 8.5. Peripheral docking/berthing mechanism: outside/inside petals, hatch opening.

Contact dynamics and shock attenuation systems are more complicated for peripheral docking systems than for central docking systems, due to the facts that the first contact will take place with peripheral systems on a point located on a circle around the docking axis with a diameter of the order of 1 m or more, and that, with the relatively large number of subsequent contacts at different places, a three-dimensional load pattern will be created. With central devices the first contact will occur at a distance from the docking axis of the order of 0.1 m, with not more than one or two subsequent contacts, which allows in many cases a representation of the contact dynamics by a two-dimensional model. Shock attenuation systems will be treated in more detail in section 8.3. As mentioned above, shock attenuation function will not be required in the case of berthing, as in this case the insertion velocities are generally very low.

8.2.3 Androgynous design of docking mechanisms

After the experience of the first manned space-flight programmes at the end of the 1960s, the idea of an androgynous docking mechanism emerged. Androgynous docking mechanisms have the same basic functions and interfaces on both sides, and both sides can play either the active or the passive role in the docking process. Androgynous design of the docking interfaces was seen as one of the prerequisites for the rescue of incapacitated spacecraft, and, further, as being able to provide increased operational flexibility, e.g. in the build-up and reconfiguration of more complex assemblies in space. A secondary effect of androgynous design is the increased reliability due to the redundancy of functions on both sides.

The price to be paid for these advantages is the increased mass, volume and complexity of the design and the according penalties on the vehicles concerning payload-carrying capability, concerning design for long term operation in space, etc. Then the question must be addressed of whether strict androgynous design is the optimal solution for all mission scenarios, or, in other words, whether there are design requirements which overrule the desire for identical functionality on both sides.

In a space station servicing scenario, the docking interfaces on the station's side may have to stay in orbit for a period of 10–20 years. Maintenance of all items of the docking mechanism facing outer space would have to be performed by extra-vehicular activity (EVA), which is not only technically difficult, but also a penalty concerning the operational resources (crew) available. It is, in this case, much better to arrange all design elements which may be sensitive to long term operation under space conditions on the side of the vehicle which is launched from ground to visit the space station. Such elements would be seals, damper elements and generally all active devices (electro-mechanical devices, lubricated bearings, etc.).

Considering the re-configuration of assemblies in space, it has to be taken into account (a) that for long term connections the priority of requirements may be different from those for a short term docking connection, and (b) that, for re-configuration, other assembly methods, i.e. berthing, may be available. In berthing, the issue of impact attenuation is of lesser importance, as we have already seen above, and bulky damper assemblies will not be necessary. If in a re-configuration two outside interfaces have to be mated, seals become a problem. However, since the connection to be made will, in such a re-configuration, be of long term nature, the potentially necessary extra effort of seal replacement by EVA would be justifiable. These few considerations show already that androgyny of the interfaces is a real advantage, although not all features of a docking mechanism need to be available in the assembly and re-configuration scenario of pressurised modules. In the design of the CBS of the ISS (see figure 8.13 below), these considerations have been taken into account.

For the rescue of incapacitated spacecraft, other overruling constraints play a role. An urgent need to bring back a spacecraft to ground exists only when it is manned. In the manned LEO scenarios, the spacecraft involved are either short term visiting vehicles or long term orbiting space stations. An orbital station needs to have a safe return vehicle attached to it, as long as it has crew aboard. The type of mating mechanism by which this return vehicle is attached is of no importance, as long as it can quickly and safely depart in emergency situations. Manned visiting vehicles have their own re-entry and landing capabilities. If such spacecraft get into serious trouble before or after visiting the station, the chance of rescue by another vehicle would be very small, even if a fully androgynous docking system were available. The reasons for this are (a) the necessity to have a second vehicle and launch facilities to be in operational readiness during the flight and (b) the unpredictable orbital and operational conditions of the spacecraft to be rescued, for which no preparation is possible. Spacecraft designers will, therefore, rather invest their development efforts in making the vehicles more reliable concerning safe return to ground than in establishing a rescue capability.

In conclusion, neither the servicing scenario nor the rescue scenario can be considered as a driver for a fully androgynous design of docking mechanism. The greatest benefits from androgynous design of a mating mechanism can be obtained in a space station assembly scenario, where re-assembly of modules during build-up or later may become necessary. Such attachment mechanisms may, however, not need to include all functions of a docking mechanism. Further, not all features of an attachment mechanism for space station modules will need to have fully androgynous design. For instance, the CBS for the ISS, described below (figure 8.13), has an active half and a passive half.

8.2.4 Unpressurised docking/berthing mechanisms

If both of the vehicles to be mated are unmanned, a pressurised transfer tunnel and hermetic seals on the interface ring are generally not needed. This will significantly reduce the complexity of the mating mechanism. In the case of berthing, the mechanism can be reduced to the function of a structural connection latch. In docking the shock attenuation and capture functions are still necessary. The latter can be combined, however, with the structural connection function.

A typical example of the basic design principles of unpressurised docking or berthing mechanisms is the V-latch arrangement shown in figure 8.6. Such an arrangement typically consists of three or four latches arranged on the mating ring of the active vehicle, with handlebars as interfaces for the latches on the side of the passive vehicle. The latch consists of a V-shaped guiding structure and two arms, which after closure will prevent escape of the handlebar and will pull it down into its seat. In docking, if contact velocities are relatively small, the damping elements can be arranged between the fixed V-shaped structure and a V-shaped guiding structure, as indicated in the figure. For larger impact velocities, spring-damper elements may have to be arranged between the latches and the base structure, e.g. in an arrangement such as in the peripheral docking systems shown below.

This type of mechanism has been used in berthing operations by the US Space Shuttle, e.g. in the servicing and repair missions for the Hubble Space Telescope, and will be used in the ISS scenario for attachment of unpressurised payloads on to the truss. For docking,

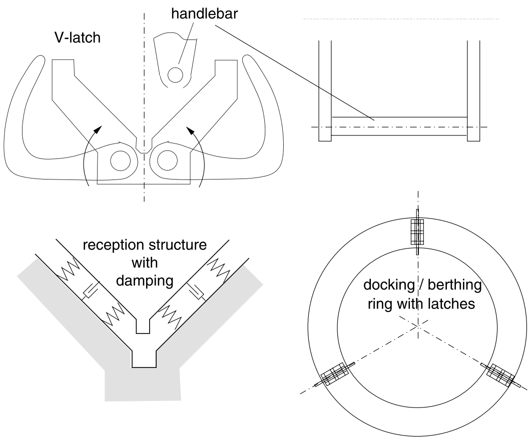

Figure 8.6. Unpressurised docking/berthing mechanism: V-latch.

this type of mechanism has been used in the rendezvous and docking demonstration of the Japanese ETS-VII mission in 1999 (Taniguchi *et al.* 1991; Ichikawa *et al.* 1993) described in section 10.7.3.

8.2.5 Examples of docking and berthing mechanisms

A few examples of previously developed docking mechanisms are described below. It is not the intention to provide here an exhaustive design description of these mechanisms, but rather to give them as examples for the requirements and features stated in the previous section. The functions of the typical elements of docking and berthing mechanisms are described in more detail in the following chapters. The first four of the examples given here are described in more detail in Syromiatnikov (1990).

The Apollo probe–drogue docking system

This is one of the first mature docking mechanism designs, and has been used in all Apollo missions in the Moon-landing and Skylab programmes.

The overall design is shown in figure 8.7. It is a central docking system of the type shown in figure 8.4, with a reception cone with a capture hole in the centre on the target side and a spherically suspended rod with shock attenuation on the chaser side. After first contact with the reception cone, the conical tip of the rod will be pushed into the capture hole. The tip is connected via a spherical bearing to the rod, allowing alignment with the surface of the reception cone. Upon entering into the capture hole, the spring-loaded capture latches on the tip of the rod will engage on the flange inside the entrance of the hole. Alignment between the two vehicles is achieved during retraction of the rod through a number of arms which form a cone and are connected to the base of the rod.

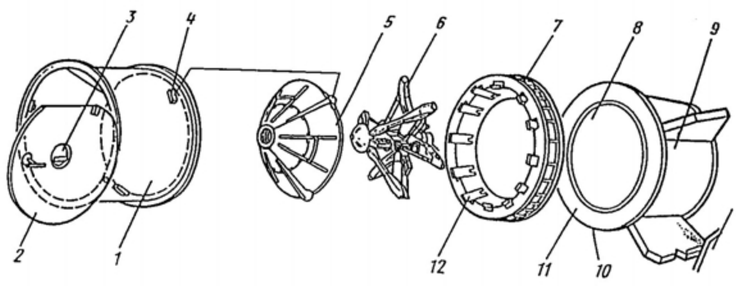

Figure 8.7. Example: Apollo docking mechanism (courtesy NASA).

Structural connection is achieved through 12 single-hook structural connection latches, which engage on the flange of the docking ring. The mechanism assembly for capture, damping and alignment has to be removed after opening of hatches to clear the transfer tunnel. The parts of figure 8.7 are as follows:

(1) docking ring of passive vehicle (on tunnel of Lunar Module),
(2) hatch of Lunar Module,
(3) valve for pressure equalisation,
(4) supports for receiving cone,
(5) receiving cone of passive vehicle,
(6) capture and alignment mechanism on active vehicle (Command Module),
(7) docking ring of active vehicle,
(8) (9), (10), (11) tunnel, hatch and sub-structure of active vehicle,
(12) structural latches of active vehicle.

The Russian probe–drogue docking system

This type of docking mechanism has been used in the Salyut and Mir Space Station scenarios for docking of the manned Soyuz and unmanned Progress spacecraft with the orbital station. It is also used in the ISS scenario for docking of the Soyuz, Progress and ATV vehicles at the Service Module side.

The first design without seals and latches for pressurised connection was developed at the same time as the Apollo system, and has been re-designed and refined thereafter during many years of application. The basic design of the system is shown in figure 8.8. It is similar to that of the Apollo probe–drogue docking system, i.e. a central docking system of the type shown in figure 8.5, with a reception cone and capture socket on the target side and a spherically suspended rod with shock attenuation on the chaser side. After first contact with the reception cone, the spherical tip of the rod will be pushed into the capture socket. Upon entering into it, the spring-loaded capture latches on the tip of the rod will engage their corresponding catches in the socket. Alignment between

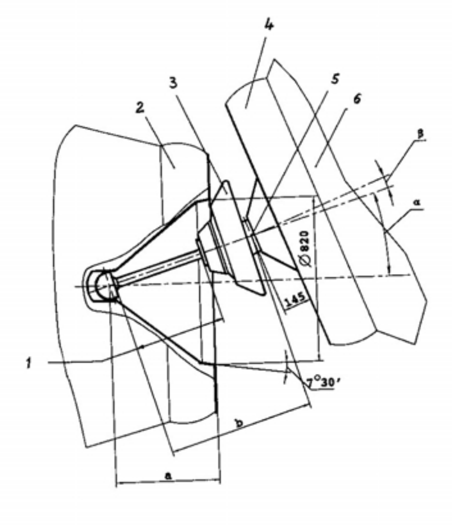

Figure 8.8. Example: Russian probe–drogue docking mechanism (courtesy RSC Energia).

the two vehicles is achieved during retraction of the rod through a convex cone (or a number of arms forming such a cone) at the base of the rod. For structural connection, double-hook type connection latches are used (see section 8.4.1). The hooks engage each other and can be operated from both the chaser and target side. As in the Apollo case, the mechanism complex for capture, damping and alignment has to be removed after opening of hatches to clear the transfer tunnel. Utility connections for power, data and fluid transfer are performed automatically. The parts of figure 8.8 are as follows:

(1) capture rod (probe) with extension stroke (in extended position),
(2) docking ring with receiving cone structure (drogue) of passive vehicle,
(3) angular limiting device,
(4) docking ring of active vehicle,
(5) spherical bearing of capture rod,
(6) substructure of active vehicle.

The Apollo–Soyuz androgynous peripheral docking system

This is the ancestor of all peripheral docking/berthing mechanisms. The two sides of the system were developed, according to a joint interface specification, independently by the USA and the Soviet Union for the Apollo–Soyuz demonstration mission in 1975. This was the first attempt to design an androgynous mechanism, i.e. each side can be active or passive, and each half mechanism could be mated with a copy of it. For the demonstration mission both sides developed its own mechanism, in which the geometry of reception petals and contact ring, capture latch and structural latch interfaces was prescribed, but most of the detailed design was at the discretion of each of the parties. In the demonstration mission, each side assumed once the active and once the passive role. In figure 8.9, the Apollo side is shown in the passive configuration with the contact ring retracted to the docking ring, and the Soyuz side is shown in the active extended configuration.

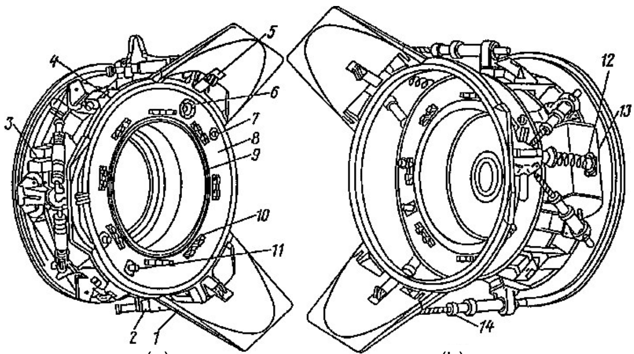

Figure 8.9. Example: Apollo–Soyuz docking mechanism assembly (courtesy NASA, RSC Energia). (a) Apollo side; (b) Soyuz side.

First contact occurs between the flanks of the three guiding petals mounted on the outside of each of the contact rings. The contact rings are separated from the structural connection ring (docking ring) by six dampers arranged in a ‘Stewart platform’ setup. On the active side, the dampers are extended; on the passive side they are retracted. Each petal carries a spring-loaded capture latch, which acts on a latch-catch on the opposite ring. After contact, the active contact ring will be pushed toward the passive one and will be aligned with it so that the capture latches will engage their corresponding catches. After successful capture, retraction of the contact ring is performed by motor drives via the damper screws on the Soyuz side and via three cables on the Apollo side. For structural connection, eight double-hook type latches of the Soyuz mechanism design described above were used. The parts of figure 8.9 are as follows:

(1) contact ring with petals,
(2) hydraulic shock attenuators,
(3) docking mechanism drive (retraction),
(4) capture latch-catch,
(5) capture latch,
(6) alignment guide socket,
(7) push rod (for separation),
(8) docking ring,
(9) seal rings,

(10) structural latches (hooks),
(11) alignment guide pin,
(12) flexible cable,
(13) differentials unit with docking mechanism drive,
(14) screw with bearing-screw converter.

The APDS Androgynous Peripheral Docking System

The APDS is an improved development of the Apollo–Soyuz docking system. It was intended originally for the Russian 'Buran' spaceplane, and an according interface was mounted on the Cristal module of the Mir Space Station. After termination of the Buran project, it was used with some modifications by the US Space Shuttle visits to Mir, and is now used for the docking of the Space Shuttle to the ISS.

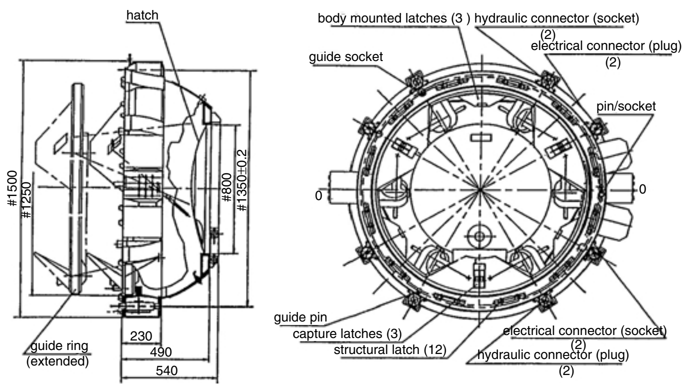

Figure 8.10. Example: APDS docking mechanism assembly (courtesy RSC Energia).

The basic functions of the APDS (see figure 8.10) are identical to those of the Apollo–Soyuz peripheral docking mechanism. First contact between the mechanism halves mounted on chaser and target will occur between the three petals mounted on the contact rings of each side. In contrast to the Apollo–Soyuz mechanism, the petals point to the inside of the docking tunnel. The contact ring (guide ring) is, as in the previous example, separated from the structural connection ring (docking ring) by a spring-damper system arranged in a 'Stewart platform' setup. In the middle of each petal is mounted a capture latch, which engages on a latch-catch, mounted on the docking ring flange of the opposite mechanism. After capture, the contact ring will be retracted using the screws of the damper elements. Because of the larger seal diameter (compared with that of the previous example), 12 double-hook type structural latches are arranged on the docking ring. Utility connections for power, data and fluid transfer are performed automatically.

The Hermes–Columbus docking system

This is an example of a peripheral docking mechanism design for very low approach velocities (0.01–0.03 m/s). Because of the discontinuation of the Hermes and Columbus

Free-Flyer Programmes, this mechanism has never been flown. However, a prototype has been built and dynamically tested (Gonzales-Vallejo *et al.* 1992). The design is discussed here because of the different design principles used for the capture and damping functions.

In this design (see figures 8.11 and 8.12), the functions of capture latch and retraction mechanism are combined. Only the active half of the docking system has capture latches and damping functions. Closure of a capture latch is initiated upon the entrance of the interface of the passive side into the reception range, which is detected by light sensors. First contact again occurs between the flanks of the guiding petals mounted either on the outside or the inside of each of the contact rings.

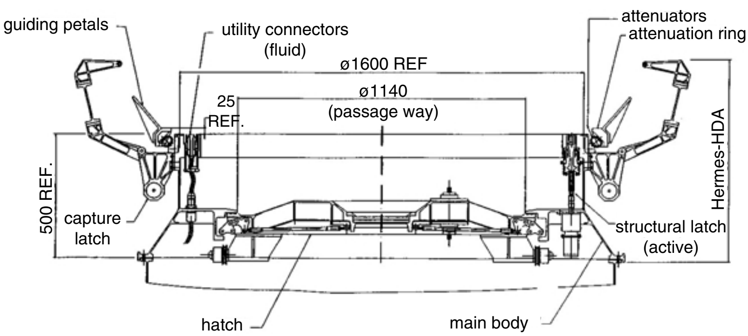

Figure 8.11. Example: Hermes–Columbus docking mechanism (courtesy ESA).

The contact ring and the structural connection ring of the active half of the system are separated by a friction damper ring. Because of the capture strategy (see section 8.3.5) and the very low approach velocity, damping by friction devices was found to be sufficient. These small devices are in the form of spring-friction coils (see figure 8.24), designed only for attenuation of the contact shock at very low velocities, but not for achieving alignment and capture. Four active capture latches are mounted either inside or outside the docking ring of the active side. Twelve structural latches of the bolt and nut type are arranged on the inside of the tunnel, i.e. inside the seals, allowing removal/replacement by intra-vehicular activity (IVA). Utility connections should be made manually after hatch opening. The type and number of latches have been chosen because of the large diameter of the sealing ring ($>$1.6 m).

The NASA ISS Common Berthing Mechanism

This mating system (see figure 8.13) has been designed for connection of large space station modules (Illi 1992). The major design requirement is a large hatch diameter, allowing the transfer of standard ISS double racks (1055×900 mm cross section). As a

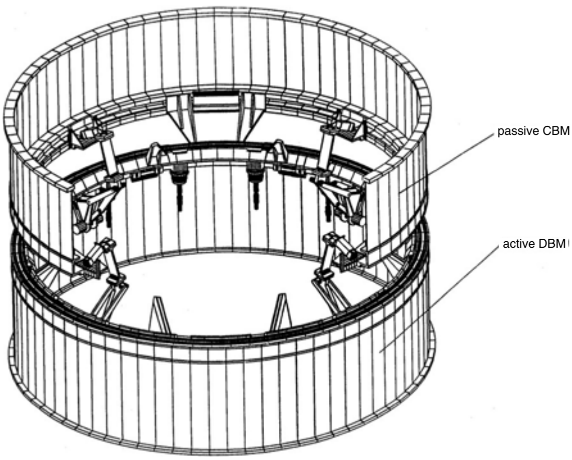

Figure 8.12. Example: Hermes–Columbus docking mechanism with inside petals (courtesy ESA).

result, the berthing ring has an inner diameter of about 1.8 m. Guiding petals are on the inside of the connection ring and can be removed after pressurisation and hatch opening. The mechanism does not need a damping function, as the insertion velocity during the manipulation is very low and as there is no limitation concerning the capture time.

Four capture latches are mounted on the inside of the connection ring, which are used for grappling the counterpart after insertion by the manipulator and fulfil the function of retraction and alignment of the two mechanism halves in preparation for structural connection. Similarly for the guiding petals, the capture latches are inside mounted, and will be removed, once long term connection has been established. Sixteen structural latches of the bolt and nut type are arranged inside the seals, allowing removal/replacement by IVA. Also, all utility connections are inside the seals, and connection will be established manually.

The NASA Low Impact Docking Mechanism

A prototype of this peripheral docking mechanism design has been developed by a team of NASA and Lockheed Martin engineers at the Johnson Space Center (JSC) for docking and berthing of the X-38 and crew return vehicles to the ISS (Lewis & Carroll 1999). An early version of this mechanism is shown in figure 8.14. The three petals for reception and mechanical guidance are directed to the inside. Along with the Stewart platform arrangement of the attenuation system they are analogue to other peripheral systems. This mating system has two interesting and novel design features: a force sensor driven, closed loop controlled electro-mechanical alignment and attenuation system with linear actuators and an electro-magnetic capture latch system.

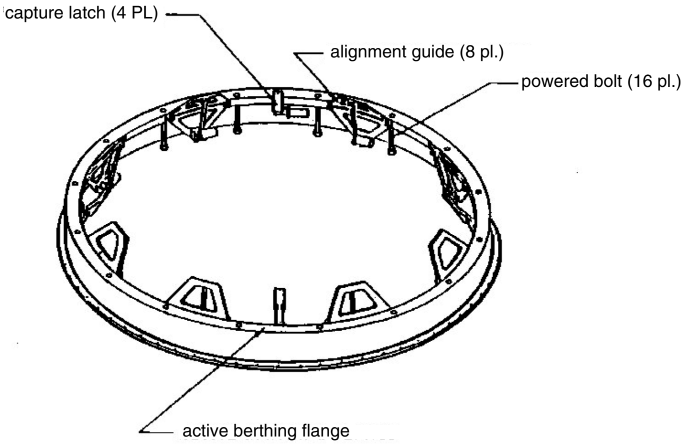

Figure 8.13. Example: ISS Common Berthing Mechanism (courtesy NASA).

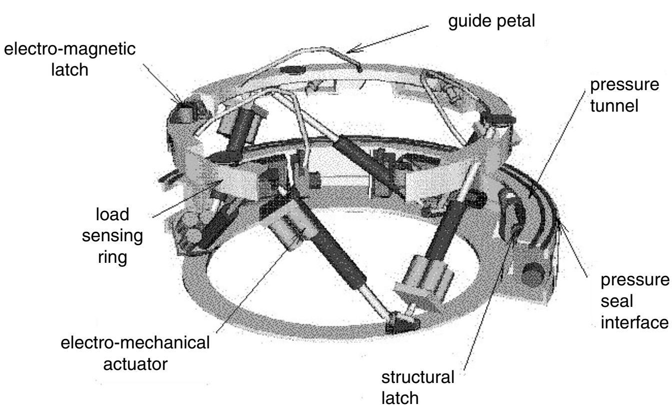

Figure 8.14. Example: cut away view of Low Impact Docking Mechanism (courtesy NASA).

At contact, the six force sensors, which are arranged at 45 deg w.r.t. the contact ring in a similar way to the linear actuators, determine magnitude and direction of the force vector and the point of force application. The control loops are closed via the six linear actuators to align the contact ring with the contact ring on the target, i.e. the forces sensed by the force sensors are balanced. At this stage, the three electromagnets are engaged to latch the contact ring of the target onto that of the chaser. The attenuation of the approach velocity is then achieved by the closed loop control system, where the required damping characteristics can be programmed into the control software. The retraction of the contact ring to join the structural connection ring with the seals is performed by further reduction of the extension of the six linear actuators.

8.3 Contact dynamics/capture

8.3.1 Momentum exchange at contact

The movement of and between two bodies after contact can be derived from the momentum law. For translational motion over the time period $\Delta t = t_1 - t_0$, the relation between the change of velocity vector $\Delta \mathbf{V}$ and the force $\mathbf{F}$ on a body with the mass m is

$$\int_{t_0}^{t_1} \mathbf{F} \mathrm{d}t = m \cdot \Delta \mathbf{V} \tag{8.1}$$

If the point of impact is not located on a line connecting the CoMs of the two bodies, the change of angular momentum must also be taken into account:

$$\mathbf{I} \cdot \Delta \boldsymbol{\omega} = \int_{t_0}^{t_1} (\mathbf{r} \times \mathbf{F}) \, \mathrm{d}t \tag{8.2}$$

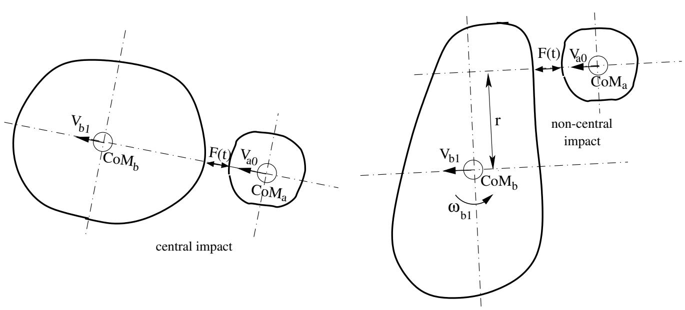

Figure 8.15. Basic relations at contact.

where $\Delta\boldsymbol{\omega}$ is the change in the angular velocity vector of the body during the time period $\Delta t = t_1 - t_0$, $\mathbf{I}$ is the inertia tensor of the body and $\mathbf{r}$ is the distance vector between the contact point and the CoM of body b. The two types of impact are shown in figure 8.15. The first one, where the line of impact forces goes through the CoMs of both bodies, is called 'central' impact; the second one with a lever arm r w.r.t. the CoM of one or both of the bodies is called 'non-central' or 'eccentric' impact.

The effects of momentum exchange at contact between two bodies can be explained most simply by examining the simplified case of an impact along one of the main axes, e.g. the x-axis. For a central impact, Eq. (8.1) becomes

$$\int_{t_0}^{t_1} F_x(t)\mathrm{d}t = m\Delta V_x \tag{8.3}$$

Considering two impacting bodies a and b with masses m_a and m_b and velocities in the x-direction $V_\mathrm{a}(t)$ and $V_\mathrm{b}(t)$, respectively, the changes of velocity due to the impact are

$$m_\mathrm{a}(V_\mathrm{a1} - V_\mathrm{a0}) = -\int_{t_0}^{t_1} F_x\mathrm{d}t \tag{8.4}$$

$$m_\mathrm{b}(V_\mathrm{b1} - V_\mathrm{b0}) = \int_{t_0}^{t_1} F_x\mathrm{d}t \tag{8.5}$$

where V_a0 is the velocity of body a at contact, t_0 is the time at contact and t_1 can be any time during the impact, i.e. before the two bodies have separated again.

The impact can be divided into two parts: a compression phase and an expansion or restitution phase. At the end of the compression phase, i.e. when the two bodies have assumed the closest distance, they have the same joint velocity $V_\mathrm{c} = V_\mathrm{a1} = V_\mathrm{b1}$. This is also the case if we assume that capture takes place, i.e. the combined body will continue to move with the common velocity V_c. As the forces acting on the two bodies are equal in magnitude, but opposite in direction, we can write for the case of a central impact

$$m_\mathrm{b}(V_\mathrm{c} - V_\mathrm{b0}) = -m_\mathrm{a}(V_\mathrm{c} - V_\mathrm{a0}) \tag{8.6}$$

$$V_\mathrm{c} = \frac{m_\mathrm{a}V_\mathrm{a0} + m_\mathrm{b}V_\mathrm{b0}}{m_\mathrm{a} + m_\mathrm{b}} \tag{8.7}$$

If capture is not successful, the forces of the springs of the spring-damper system of the docking mechanism will cause the two vehicles to separate again after the impact.

For a non-central impact, let us consider again the simple case of an impact of body a on body b with a velocity V_a in the x-direction, where on body a the force line passes through the CoM, but where on body b a distance r exists in the y- or z-directions between the impact line and the CoM. Assuming further that the value of r will not change during the time $t_1 - t_0$, the angular momentum Eq. (8.2) for body b becomes

$$I_\mathrm{b} \cdot (\omega_\mathrm{b1} - \omega_\mathrm{b0}) = r \cdot \int_{t_0}^{t_1} F_x(t)\mathrm{d}t \tag{8.8}$$

For simplicity, we also assume that

$$V_{\mathrm{b0}} = 0 \tag{8.9}$$

$$\omega_{\mathrm{b0}} = 0 \tag{8.10}$$

At the end of the compression phase, or at the instant of capture, both bodies have, at the contact point, the same velocities, where on body b the velocity is the sum of a translation of the CoM and of an additional translation of the impact point due to the induced angular velocity about the CoM:

$$V_{\mathrm{c}} = V_{\mathrm{a1}} = V_{\mathrm{b1}} + r \cdot \omega_{\mathrm{b1}} \tag{8.11}$$

Whereas the momentum equation for body a is still Eq. (8.4), for body b the two equations (8.5) and (8.8) have to be considered for the momentum exchange. They become, with the initial conditions (8.10):

$$m_{\mathrm{b}} V_{\mathrm{b1}} = \int_{t_0}^{t_1} F_x \mathrm{d}t \tag{8.12}$$

$$\frac{I_{\mathrm{b}}}{r} \omega_{\mathrm{b1}} = \int_{t_0}^{t_1} F_x \mathrm{d}t \tag{8.13}$$

From these equations, and with Eqs. (8.4) and (8.11), one obtains for the translational motion of body b

$$V_{\mathrm{b1}} = V_{\mathrm{a0}} \frac{I_{\mathrm{b}} \cdot m_{\mathrm{a}}}{I_{\mathrm{b}}(m_{\mathrm{b}} + m_{\mathrm{a}}) - r^2 m_{\mathrm{a}} m_{\mathrm{b}}} \tag{8.14}$$

and, for the angular motion,

$$\omega_{\mathrm{b1}} = V_{\mathrm{a0}} \frac{r \cdot m_{\mathrm{a}} \cdot m_{\mathrm{b}}}{I_{\mathrm{b}}(m_{\mathrm{b}} + m_{\mathrm{a}}) - r^2 m_{\mathrm{a}} m_{\mathrm{b}}} \tag{8.15}$$

In a real case, the impact will not be along one of the main axes, nor will the docking axis necessarily go through the CoM. To calculate the impact forces and the dynamic reactions of the two vehicles during and after contact, the exact point of contact and the angles of the impact line w.r.t. the body coordinates of the two spacecraft will have to be determined as a first step. The details of these calculations depend on the geometry of the vehicles and their docking interfaces, and on the state vectors of both spacecraft. Because of the complex geometrical relations at contact, they will become quite elaborate. However, for a basic understanding of the contact and capture processes, they are not needed here.

8.3.2 Shock attenuation dynamics

If two compact bodies impact with each other, the elastic and/or plastic deformations will be relatively small, depending on the material properties. As a result, the impact time will be relatively short, and accordingly the forces will be relatively high. For docking of two spacecraft, this would have as a consequence high structural loads and a very short time for capture. In order to reduce contact forces and to increase the time available for capture, shock absorber devices are applied in the docking mechanism which are designed to increase the amount of travel after contact due to elastic and plastic deformation and to absorb a part of the kinetic energy by viscous damping and/or friction. In both cases, velocity proportional damping or constant friction, a part of the kinetic energy of the relative motion is converted into heat.

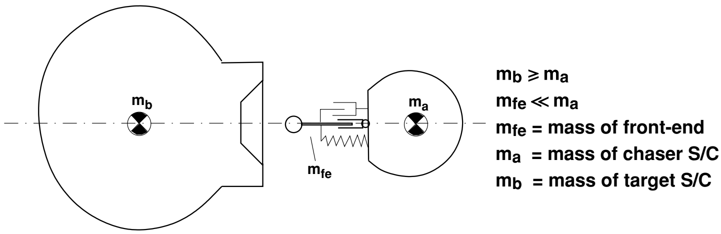

Figure 8.16. Simplified model: central impact with spring-damper system.

The function of shock attenuation systems for spacecraft mating can be best explained using the above simple example of a central impact along the x-axis of two impacting bodies and putting a shock attenuator in between (see figure 8.16). As a rule, shock attenuation systems consist of elastic elements, i.e. springs, and elements converting the motion energy into heat. The mass of the shock absorber system is assumed to be very small compared with the masses of each of the vehicles. The energy conversion functions are known as dampers, which can be implemented either as velocity dependent friction devices, as constant friction devices or as a combination of both. Velocity dependent friction devices can be, e.g., viscous dampers, where a fluid is pressed through a narrow gap or orifice and the resistance force is dependent on the speed through the gap, or, e.g., eddy current dampers, where the resistance torque is dependent on the angular velocity of a metal disc rotating in a magnetic field.

The equation of motion of a mass connected via a spring and a velocity proportional damper to a fixed point in an inertial frame is

$$F_x(t) = m\,\ddot{x} = -D\dot{x} - Cx \pm F_{\mathrm{f}} \tag{8.16}$$

where D is the damping constant, C is the spring constant and F_{f} is the constant friction force. The sign of the friction force is always opposite to the direction of motion.

For the case that two masses m_{a} and m_{b} are connected by a spring and viscous damper system (figure 8.16), the equations of motion are, for body a,

$$m_{\mathrm{a}}\,\ddot{x}_{\mathrm{a}} = -D\Delta\dot{x} - C\,\Delta x \tag{8.17}$$

and, for body b,

$$m_{\mathrm{b}}\,\ddot{x}_{\mathrm{b}} = +D\Delta\dot{x} + C\,\Delta x \tag{8.18}$$

where $\Delta x = x_1 - x_0$ is the distance and $\Delta \dot{x} = \dot{x}_1 - \dot{x}_0$ is the relative velocity between the two bodies. Subtraction of these equation yields

$$\Delta \ddot{x} = \ddot{x}_1 - \ddot{x}_0 = -(D\Delta \dot{x} + C\,\Delta x)\left(\frac{1}{m_\mathrm{a}} + \frac{1}{m_\mathrm{b}}\right)$$

which can be written as

$$\Delta \ddot{x} = -(D\Delta \dot{x} + C\,\Delta x)\frac{1}{m_\mathrm{e}} \tag{8.19}$$

where m_e is the equivalent mass of the system:

$$m_\mathrm{e} = \frac{m_\mathrm{a} \cdot m_\mathrm{b}}{m_\mathrm{a} + m_\mathrm{b}} \tag{8.20}$$

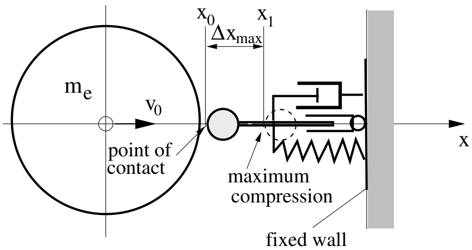

Figure 8.17. Simplified equivalent mass model for central impact.

The simplified spring-damper model with an equivalent mass is shown in figure 8.17. This definition has the advantage that only the relative motions between the two masses need to be considered, not the motions of the individual masses w.r.t. any other frame, e.g. related to pre-contact conditions. The definition of an equivalent mass is also valid for a constant friction damper system, as can be easily derived. Eq. (8.16) shows that there are several possible ways of reducing the kinetic energy $(1/2 \cdot m\dot{x}^2)$:

- by a spring,
- by solid friction braking,
- by velocity proportional braking,
- by a combination of two or all of these functions.

Shock attenuation by spring only

For this case the equation of motion becomes

$$m_\mathrm{e}\ddot{x} = -Cx \tag{8.21}$$

The well-known solution of this differential equation is

$$x(t) = c_1 \cos \omega_1 t + c_2 \sin \omega_1 t \tag{8.22}$$

where the resonant frequency $\omega_1 = \sqrt{C/m_\mathrm{e}}$. The constants can be obtained from the boundary conditions for t_0:

$$c_1 = x_0; \quad c_2 = \frac{v_0}{\omega_1} \tag{8.23}$$

Damping by solid friction braking only

For this case the equation of motion becomes

$$m_\mathrm{e}\ddot{x} = \pm F_\mathrm{f} \tag{8.24}$$

The direction of the friction force is always opposite to the direction of the velocity. The solution for the travel over time can be found easily by double integration:

$$x(t) - x_0 = \Delta x(t) = \left(v_0 \pm \frac{F_\mathrm{f}}{2m_\mathrm{e}} t\right) t \tag{8.25}$$

The equation is valid up to the time where $\mathrm{d}x/\mathrm{d}t$ becomes zero.

Damping by velocity proportional braking only

For this case, the equation of motion becomes

$$m_\mathrm{e}\ddot{x} = -D\dot{x} \tag{8.26}$$

This equation can easily be integrated once. Thereafter, the solution for the travel over time can be obtained, using the homogeneous solution ($y = c\cdot$) of a first order linear differential equation $\exp\left(\int_p dt\right)$ ($\dot{y}+py = 0$). With the substitutions $D/m_\mathrm{e}x(t)-c_1 = y$ and $D/m_\mathrm{e} = p$, the equation can be brought into the above form, yielding the following result:

$$x(t) - x_0 = \Delta x(t) = -\frac{m_\mathrm{e}}{D} v_0 (\mathrm{e}^{-\frac{D}{m_\mathrm{e}} t} - 1) \tag{8.27}$$

Combination of a velocity proportional braking device and spring

For this case the equation of motion becomes

$$F_x(t) = m\,\ddot{x} = -D\dot{x} - Cx \tag{8.28}$$

Solutions are available for this type of differential equation, if it is written in the following form:

$$\ddot{x} + 2\delta\dot{x} + \omega_1^2 x = 0$$

where the coefficients are $\omega_1^2 = C/m$ and $2\delta = D/m$. The constant ω_1 is again the resonant frequency of the spring–mass system. The solutions are

$$x(t) = \mathrm{e}^{-\delta t}(k_1 \cos \lambda t + k_2 \sin \lambda t) \;\text{ for } \lambda^2 = \omega_1^2 - \delta^2 > 0 \tag{8.29}$$

$$x(t) = \mathrm{e}^{-\delta t}(k_1 \cosh \lambda t + k_2 \sinh \lambda t) \;\text{ for } \lambda^2 = \omega_1^2 - \delta^2 < 0 \tag{8.30}$$

$$x(t) = \mathrm{e}^{-\delta t}(k_1 + k_2 t) \;\text{ for } \lambda^2 = \omega_1^2 - \delta^2 = 0 \tag{8.31}$$

The first case represents an oscillation with low damping, the second one with high damping and the last one is the boundary case of aperiodic damping. This third case, where $\omega_1^2 = \delta^2$, is the optimal case for avoidance of oscillations. This condition will in real cases never be met exactly, but it is very useful as a reference case for the assessment of spring-damper systems, as it leads to simple mathematical expressions which can be quickly evaluated. The constants k_1 and k_2 can easily be determined from the boundary conditions:

$$\begin{aligned} k_1 &= x_0 \\ k_2 &= v_0 + \delta x_0 \end{aligned} \tag{8.32}$$

where Δx_0 and v_0 are the conditions at the start of the motion. With these constants, and using the definitions of Eqs. (8.19) and (8.20), the equations for the relative position Δx (from Eq. (8.31)), the relative velocity $v = \Delta\dot{x}$, and the relative acceleration $\Delta\ddot{x}$ between the two bodies after contact become

$$\Delta x(t) = \mathrm{e}^{-\delta t}[\Delta x_0 + (v_0 + \delta\Delta x_0)t] \tag{8.33}$$

$$\Delta\dot{x}(t) = \mathrm{e}^{-\delta t}[v_0 - (v_0 + \delta\Delta x_0)\delta t] \tag{8.34}$$

$$\Delta\ddot{x}(t) = \delta\mathrm{e}^{-\delta t}[(v_0 + \delta\Delta x_0)\delta t - 2v_0 - \delta\Delta x_0] \tag{8.35}$$

For our application, Δx_0 is always zero, as the spring-damper system is in a neutral position at the instant of contact. The maximum possible compression, Δx_{max}, shown in figure 8.17, is a constraint imposed by the design of the system; it is not the maximum excursion due to the dynamics of the impact. In fact, the spring-damper parameters, including the maximum possible excursion, have to be chosen such that they are valid for all dynamic conditions potentially occurring in a particular mission scenario.

The definition of the factor δ for the aperiodic case according to Eq. (8.31) is

$$\delta = \omega_1 = \sqrt{\frac{C}{m_{\mathrm{e}}}} \tag{8.36}$$

From Eqs. (8.33), (8.34) and (8.35) the relative motion and force over time between the two bodies can easily be calculated. For the central impact case, the force acting between the two sides is according to Eq. (8.28) and the definition of the equivalent mass in Eq. (8.20):

$$F_x(t) = m_{\mathrm{e}}\Delta\ddot{x}$$

8.3.3 Example case for momentum exchange and shock attenuation

Let us consider two spacecraft, which are docking with the following impact conditions:

- the chaser has mass $m_\mathrm{a} = 10 \times 10^3$ kg;
- the target has mass $m_\mathrm{b} = 100 \times 10^3$ kg;
- the target has an inertia about the y-axis of $I_{yy} = 10 \times 10^6 \,\mathrm{kg\ m}^2$;
- the approach velocity is $V_{\mathrm{a}1} = v_0 = 0.1$ m/s;
- the target has no velocities w.r.t. the reference frame, i.e. $v_{\mathrm{b}1} = 0$ and $\omega_{\mathrm{b}1} = 0$.

Momentum exchange

For a central impact, the joint velocity after capture is, according to Eq. (8.7),

$$V_\mathrm{c} = \frac{m_\mathrm{a} V_{\mathrm{a}0} + m_\mathrm{b} V_{\mathrm{b}0}}{m_\mathrm{a} + m_\mathrm{b}} = 0.0091\,\mathrm{m/s}$$

The change in velocity of the combined target and chaser vehicle after docking is, in this example case, not very large. However, a velocity change of the order of 0.01 m/s results in an orbital motion of the combined spacecraft w.r.t. the original target position, as shown in figure 3.10, i.e. an advance of the order of 170 m per orbital revolution. In a non-central impact case, if we assume the impact line has a distance of $r = 10$ m to the CoM, the angular velocity induced on body b is, according to Eq. (8.15),

$$\omega_{\mathrm{b}1} = V_{\mathrm{a}0} \frac{r \cdot m_\mathrm{a} \cdot m_\mathrm{b}}{I_\mathrm{b}(m_\mathrm{b} + m_\mathrm{a}) - r^2 m_\mathrm{a} m_\mathrm{b}} = 10^{-3}\,\mathrm{rad/s} = 0.057\,\mathrm{deg/s}$$

The resulting angular velocity of the target vehicle is, in this example, very small and could easily be handled by the attitude control system.

Shock attenuation

The equivalent mass of the system is, according to Eq. (8.20),

$$m_\mathrm{e} = \frac{m_\mathrm{a} \cdot m_\mathrm{b}}{m_\mathrm{a} + m_\mathrm{b}} = 9091\ \mathrm{kg}$$

In the following, shock attenuation characteristics with different types of attenuators are discussed.

Spring only attenuator Selecting a spring constant of $C = 90.91$ N/m, the resonant frequency becomes

$$\omega_1 = \sqrt{\frac{C}{m_\mathrm{e}}} = 0.1\,/\mathrm{s}$$

With the selected value for ω_1 and with the constants $c_1 = x_0 = 0$ and $c_2 = v_0/\omega_1 =$ 1.00 m, Eq. (8.22) becomes

$$x(t) = 1\sin\,(0.1t)\ \mathrm{m}$$

The result is shown in the left hand curve of figure 8.18. The maximum excursion of 1 m is reached after approximately 16 s, and the reception range is left again after approximately 31 s.

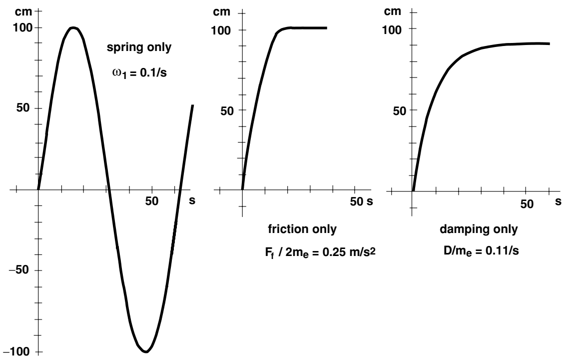

Figure 8.18. Travel after impact for spring only, friction only and damper only cases.

Friction only attenuator To achieve an attenuation curve which is comparable to the others, a factor of $F_\mathrm{f}/2m_\mathrm{e} = 0.0025\mathrm{m/s}^2$ has been chosen, which, for the equivalent mass of 9091 kg, corresponds to a friction force of $F_\mathrm{f} = 45.5$ N. With the boundary conditions $v_0 = 0.1$ m/s and $x_0 = 0$, Eq. (8.25) becomes

$$x(t) = 0.1t - 0.0025t^2\ \mathrm{m}$$

(valid for $\mathrm{d}x/\mathrm{d}t > 0$). The result is shown in the centre curve of figure 8.18. The curve is parabolic up to its maximum, where $\mathrm{d}x/\mathrm{d}t = 0$, and continues with $x(t) =$ const. With the chosen friction force the maximum excursion is, as in the previous case, 1 m, which is reached after 20 s. The curve shows also that, due to the quadratic term in Eq. (8.25), the maximum braking effect occurs only toward the end. This makes the pure friction damper quite sensitive to parameter uncertainties. Such uncertainties may be due to friction at the start of motion and to variations of friction coefficient as a function of the surface properties.

Viscous damping only attenuator The damping factor has been chosen to be $D/m_e = 0.11$ 1/s, which for the chosen mass m_e corresponds to a damping constant of $D = 1000$ kg/s. This is half of the amount used in the next case of an aperiodic spring-damper system, but leads, concerning the maximum excursion, to more comparable results with the two previous cases. Equation (8.27) becomes, with $v_0 = 0.1$ m/s and $x_0 = 0$,

$$x(t) = -9.1 \times 0.1(\mathrm{e}^{-0.11t} - 1)\ \ \mathrm{m}$$

The right hand curve in figure 8.18 shows the advantage of velocity proportional damping over friction damping. The maximum excursion is reached after approximately 40 s and the velocity is reduced steadily. This behaviour is much less sensitive to parameter uncertainties than that owing to the pure friction case.

Aperiodic spring – viscous damper The coefficient δ is, for the aperiodic case, equal to the resonant frequency, i.e. $\delta = \omega_1 = 0.1$/s, which corresponds to a damping factor of $D = 2000$ kg/s. With v_0 = 0.1 m/s and $x_0 = 0$, we obtain from Eqs. (8.33)–(8.35) the behaviour over time for the relative distance, the relative velocity and the relative deceleration between the vehicles. The results are shown in figure 8.19.

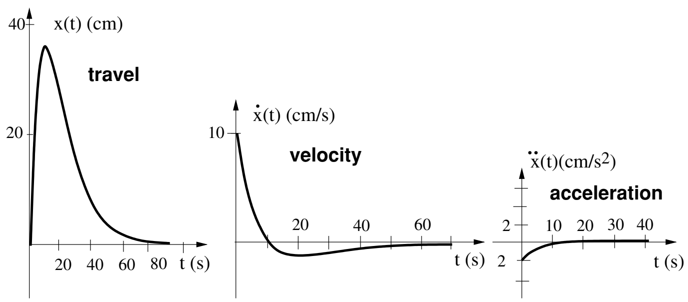

Figure 8.19. Travel, velocity and acceleration after impact for spring-damper case.

With the chosen parameters, the maximum travel of the spring-damper system is about 0.37 m after 10 s. The maximum deceleration at the beginning of the impact is 0.02 m/s^2, which is reduced to <0.004 m/s^2 after 20 s. The maximum force at the beginning of the impact is, in this example,

$$\Delta\ddot{x} \cdot m_e = 0.02\ \mathrm{m/s^2} \times 9091\ \mathrm{kg} = 181.82\ \mathrm{kg\ m/s^2}$$

The force of 182 N is equivalent to that of a thruster, which is very small for a docking impact. The maximum time available for capture can be assumed to be the time at which the contact surface of body a (in figure 8.16 the body with the mass m_e) has moved back beyond the position x_0. In figure 8.19, this time is determined by the crossing with the x-axis of the tangent through the inflection point of the $x(t)$-curve, as the bodies would separate with the maximum negative velocity gained during expansion. In our example, this time would be about 40 s.

The example shows that, with the chosen parameters, the available capture time is very long and the maximum forces are very low. This is at the expense of a large excursion of the spring-damper system, which would require a mechanism of large dimensions, resulting in an unnecessary mass and volume penalty to the spacecraft. Increasing the spring constant by a factor of 25, the parameter δ would be increased to $\delta = 0.5$, which would result in a maximum excursion of the spring-damper system of 0.075 m, in a maximum time available for capture of approximately 8 s and a maximum deceleration at start of impact of 0.1 m/s^2. Both capture time and maximum acceleration are still comfortable, but the necessary size of the mechanism can be decreased by a factor of 5.

Comparison of attenuator types

On comparing the different types of attenuators, the following conclusions can be drawn:

- A spring alone is an effective attenuator in its first quarter of oscillation. It will, however, change direction of motion after its maximum excursion and would eventually push the interfaces out of the reception range. If the time available for capture is long and the contact forces low, the resonant frequency needs to be low and the maximum excursion will be accordingly large.

- Solid friction can be easily made use of in attenuation devices; in fact, the friction present in practically all mechanisms can be included in the attenuation process. As a 'stand-alone' attenuator, however, it will be less suitable, because of its sensitivity to parameter variations.

- The velocity proportional damper is a very effective 'stand-alone' attenuator with smooth braking characteristics over time (with low decelerations). In contrast to all attenuators including a spring, it does not change its direction of motion. This makes it particularly suitable for motion braking prior to capture.

- The aperiodic spring-damper combination cancels all oscillations within the first cycle. For systems where capture is initiated immediately after entering the reception range, this attenuator type offers the combination of optimal oscillation damping with shorter excursion than the other types. For systems where capture is initiated toward the end of the excursion, the characteristics of this attenuator type are suitable for damping of the residual motion after capture.

As all of the attenuator types are obviously sensitive to the value of the initial contact velocity, the actual excursion after contact remains uncertain. This could cause a 'hard' impact if the excursion stroke available from the mechanism is smaller than the maximum excursion of the natural motion according to the contact velocity. For this reason, a type of progressive spring function in the form of a stack of springs with increasing spring constant is implemented in many designs.

It must be kept in mind that the simplified one-dimensional model with a single 'equivalent' mass, used here for the discussion of attenuation behaviour, can provide no more than an idea of the real dynamic processes and only a rough order of magnitude of the expected forces, excursions and duration. Results of this simplified model can be used to assess the preliminary design of an attenuation system concerning the necessary stroke, spring and damping constants, etc. The reality, involving six DOF motion, multiple masses, inertias and flexibilities, leads to very complex models, which can only be evaluated numerically (e.g. using the Runge–Kutta integration method) by means of computer simulation programs.

8.3.4 Devices for shock attenuation and alignment for capture

Shock attenuation systems for central docking systems

As the active part of a central docking system is a rod which is elastically connected to the main body of the chaser, two main forces will occur at contact: a longitudinal force along the rod axis; and a lateral force which causes a torque about the connection point at its base. Accordingly, a longitudinal motion, i.e. a compression (and later, if there is a spring, an expansion) along the rod axis and an angular motion of the rod about the spherical bearing at its base have to be attenuated. The damping of the longitudinal motion can be performed with one of the damper types discussed above. For the damping of the angular motion of the rod in two directions, a system with possibly three or four linear damper elements in a plane normal to the rod axis can be used (see figure 8.20).

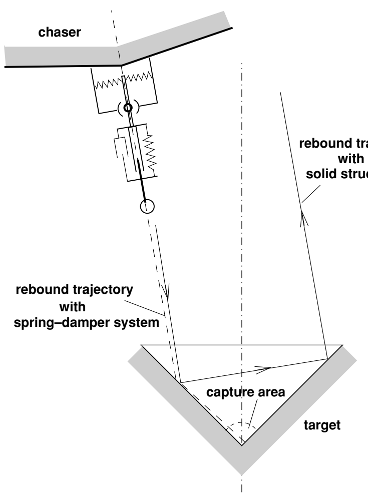

Figure 8.20. Central docking system: rebound with and without spring-damper.

Without any flexibility in the rod, in particular in its lateral direction, the tip of the rod would not move to the centre of the cone, which is the place where it can be captured. If the rod were rigid and firmly connected to the chaser body, its tip would behave as the contact point in a non-central impact according to Eqs. (8.14) and (8.15). In a cone, two rebounds with opposite translational and rotational motions would take place, as shown in figure 8.20. With axial and lateral flexibility and damping, the tip of the rod will move into the capture area in the centre of the cone.

As we have seen in Eqs. (8.25) and (8.27), motion attenuation in a longitudinal direction does not necessarily require the inclusion of springs. In fact, for capture it may be better, at least during the initial part of motion, to have only velocity proportional braking. A spring system could push the capture interfaces back after maximum excursion, if the system was not properly tuned for aperiodic damping. For the final part, in particular for damping of the residual motion after capture, spring-damper combinations, possibly together with solid friction devices, can be used.

Shock attenuation systems for peripheral docking systems

Shock attenuation and alignment for capture is, in peripheral docking systems, much more complex than that for central ones. Without damping, the motion reaction of two rings impacting on each other would be similar to the conical motion of a coin being dropped on a surface. Since the contact conditions also include lateral velocities, linear and angular misalignments and angular velocities, in addition to the velocity along the nominal approach axis, the docking system requires damper arrangements for motion in six DOF.

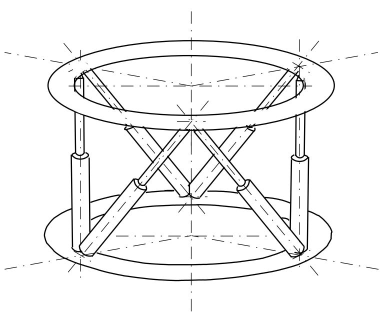

Figure 8.21. Stewart platform damper arrangement for peripheral docking mechanism.

The most commonly used arrangement used for this purpose is that of a 'Stewart platform', i.e. an arrangement of six linear motion elements, connected to three points each on the upper and lower rings (figure 8.21). The position of the connecting points between the two rings are shifted by 60 deg. This arrangement allows the use of six identical linear damper elements, and it fulfils the requirements of six DOF motion. It also provides the necessary freedom of the tunnel area for transfer of astronauts and goods.

Docking dynamics with a peripheral system are also more complex because of the following effect. If passive capture latches are used on a peripheral system, capture will take place only once the two contact rings are aligned within very small margins, i.e. the above-mentioned conical motion must be fully damped out. In contrast, in a central docking system, the tip of a flexible rod will be pushed into the centre of the reception cone, where it can be captured by passive spring-loaded latches without prior alignment of the contact rings.

In order to achieve proper alignment of the two contact rings in a very short time, either the damper elements must initially be very 'soft', or the alignment must be achieved by active means. To achieve a very soft spring behaviour for alignment and a sufficiently strong spring behaviour for shock attenuation after capture, springs can be staged in several steps with increasing spring constant. To support actively the alignment of the contact rings, the APDS docking mechanism (figure 8.10) uses a complex system of differential gears, which ensures that when the contact ring is pushed down at a certain point, its opposite side will be moved up. The concept of an actively closed loop controlled alignment system has been used in the Low Impact Docking System shown in figure 8.14. The problem of accurate alignment of the contact rings to achieve capture can be avoided when active capture latches are used, as these ensure the condition of 'no escape' prior to full alignment (see section 8.3.5).

Shock attenuation elements

A few examples of typical concepts of damping elements are given below to illustrate how such functions can be implemented. Formulas describing their operation are not provided here, as this would go beyond the objectives of this chapter. They can be found in relevant textbooks on physics.

Velocity proportional viscous damper A combination of spring and hydraulic damper is the most common damping device in many applications. It is a well known system, used e.g., as shock absorbers for cars. In ground applications, a viscous damper is designed in most cases as a piston in a cylinder, where the gap between the piston and the wall is the flow restrictor. In space applications, this type of design is less suitable because of the sealing problems. A hermetically sealed viscous damper design can be achieved, e.g., by an arrangement of two bellows, connected by an orifice, as shown in figure 8.22. The orifice between the bellows is acting in this case as the flow restrictor, providing the velocity proportional damping. The bellows themselves provide a spring force, which acts in parallel to the spring arranged on the outside.

One problem with the bellow arrangement is that the ratio of extended to compressed length is relatively small. For applications where dampers with long excursions are needed, either the piston–cylinder principle would have to be used, with the sealing

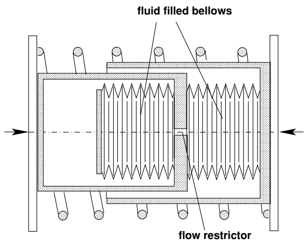

Figure 8.22. Principle of a spring viscous damper with bellows.

problem to be solved in some way, or a ‘dry’ solution may be applied, as described below.

Velocity proportional eddy current damper One way of realising a velocity proportional damper without using a liquid or gas is to use an eddy current using a damper. This principle uses the physical effect that eddy currents are induced in a piece of metal when the metal is moved in a magnetic field, and that these eddy currents interact with the magnetic field. As a result, energy is dissipated, and a magnetic drag force proportional to the velocity is produced; this tends to slow down the motion of the piece of metal.

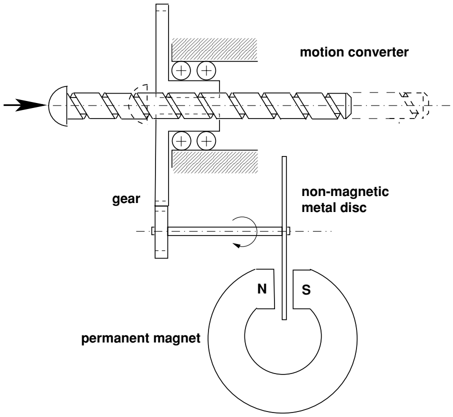

Figure 8.23. Translational/rotational motion converter and eddy current brakes.

This principle may be used to damp translational motions and may be envisaged in the way shown in figure 8.23. To produce a high damping effect, the relatively slow translational motion is converted into a rotation by a screw type of motion converter, which drives a metal disc, moving through the gap of a permanent magnet. Instead of an arrangement with a flat disc, moving in the planar gap between the poles of a magnet, an arrangement with a thin-walled metal cylinder rotating in the cylindrical gap formed by the magnet poles could be used. The latter variant is used in the Soyuz/Progress probe–drogue docking mechanism (see figure 8.8).

Friction damper Solid friction is present in practically all mechanisms; in most cases it is caused by sliding or rolling friction in the bearings. As the friction force is proportional to a compression force normal to the sliding plane, friction dampers can be implemented, e.g., by moving a disc between two others which are compressed by spring pre-load. As in the eddy current damper, the relatively slow translational motion can be converted into a rotation. The amount of friction in a friction brake can be adjusted by spring pre-load. A typical design comprises a number of rotating discs running between fixed ones, i.e. an assembly similar to a clutch.

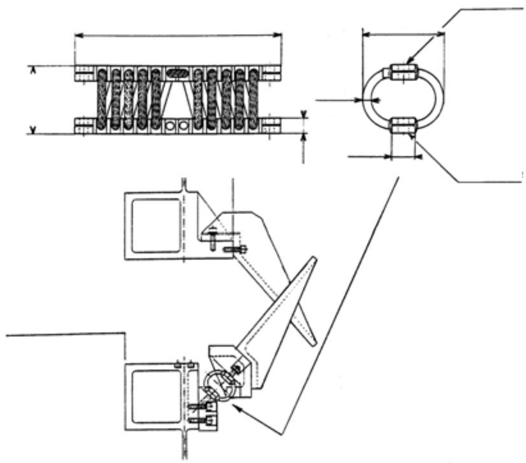

Figure 8.24. Example: friction coil element (of figure 8.11).

A different implementation of a friction damper is shown in figure 8.24 (Gonzales-Vallejo *et al.* 1993). It consists of coils of multiply twisted steel wires that rub against each other when the coils are deformed. This type of damper is used in machines for vibration attenuation. In docking mechanisms it has been implemented and successfully tested in the Hermes–Columbus docking system shown in figure 8.11. Since it allows for only relatively small deformations, this type of damper can be used only in systems with very low impact velocities.

Actively controlled motion damping The concept of a fully active alignment of the contact rings and damping of the motion by a closed loop control system has been used in the NASA development of the Low Impact Docking System (Lewis & Carrol 1999), which has been described in section 8.2.5 and is shown in figure 8.14. In this system, the force vector and its application point is actively sensed by six load cells at the circumference of the contact ring, and damping and alignment is provided by motion control of the six linear actuators arranged in a Stewart platform configuration. The advantages of an active control of alignment and attenuation may have to be paid for by increased complexity and development effort.

The advantage of a system where attenuation is realised by a closed loop controlled electro-mechanical system, including force sensors, controller and linear actuators, is in the wide range of damping characteristics which can be achieved by a change of algorithm and parameters in the control software for this system. For instance, with a closed loop controlled system, a progressive spring-damper behaviour can be achieved, which otherwise would require a series arrangement of several sizes of spring-damper elements or combinations with friction dampers.

8.3.5 Capture devices

Capture strategies

In the above discussion on impact attenuation, it has been assumed that capture will take place somewhere in the period between the first contact and the instant where, in the expansion phase, the docking interfaces of the two vehicles have again left the contact position x_0. In the following, capture issues will be elaborated upon in more detail. The actual point in time where capture should take place during the docking or berthing process depends on the capture strategy chosen. The following capture strategies can be applied.

Capture after first contact In this case, capture operations are initiated at or after the first contact between the according docking interfaces of chaser and target. Three subcases can be distinguished:

- The capture latch is effected by the kinetic energy of the docking vehicles. The capture process is similar to a door latch falling into its catch. This type of latch requires a minimum contact velocity for successful capture to overcome friction and spring forces of the mechanical guides and latches. Capture has to take place before the attenuation system has reached its maximum compression state.

- The capture latch is motor driven, and the motor operation is initiated by an impact sensor. Capture has to take place in the time period between contact and separation, i.e. the speed of latch closure must be fast enough to ensure capture before the docking interfaces have separated again.

- The contact rings will be actively aligned after the first contact and capture takes place, when the alignment conditions are achieved. Capture has to take place before the attenuation system has reached its maximum compression state.

Capture before first contact This strategy requires, in any situation, a sensor function which identifies the entrance of the interfaces into the capture range. Such sensors can be light-barrier detectors, electro-magnetic or capacitive proximity sensors, etc. The optical rendezvous sensor could be used, if it is sufficiently accurate. In the case of berthing, human operators, with the aid of manipulator cameras, may fulfil the sensor function. Two cases can be distinguished for the strategy of 'capture before contact', i.e. the typical capture operations for berthing and the capture operations of an 'intelligent docking mechanism':

- Capture for berthing: the end-effector of the manipulator actively pursues and grapples the capture interface of the other vehicle. As we have seen in section 8.1.3, these operations must be completed within 1 or 2 minutes before the vehicle to be captured has left the berthing box.

- Capture for docking by motor driven latch: this is initiated upon sensing of the docking interfaces entering into reception range. As in the case of capture after contact (above), the speed of latch closure must be fast enough to ensure capture before the docking interfaces have separated again. The advantages of this case would be, however, that about double the time is available for the capture operations, and no precise alignment of the contact rings is necessary prior to engagement of the capture latches.

The choice of capture strategy is one of the most important design drivers for the design of a mating system. It will depend on issues such as the GNC performance and vehicle velocity at contact, availability and reliability of sensor information on the capture interface position, availability of a manipulator on either chaser or target, etc.

Types of capture systems

Capture mechanism for central docking systems Because of their basic design principle, central docking systems generally follow the strategy of 'capture after first contact'. As we have seen in figure 8.20, contact will occur somewhere on the surface of the reception cone, whereafter the tip of the rod will move toward the centre of the cone, where it will be captured. Capture is achieved by spring-loaded latches arranged on the tip of the rod, which fall into their corresponding catches in the socket at the centre of the cone, as shown in figure 8.25. In order to overcome the friction and spring forces of the capture latches, this system requires a minimum kinetic energy for successful capture. For this reason, this type of docking is known as 'impact docking'. Usually, an additional thruster boost will be applied to drive the capture latches into their catches. There may be three or four latches on the tip of the rod. The catches on the opposite side will provide sufficient oversize to account for all possible misalignments. They will provide coarse limitations for translational motion and will prevent large roll motion after capture. For release and separation of the probe from the drogue, the spring-loaded capture latches can be withdrawn by a release mechanism.

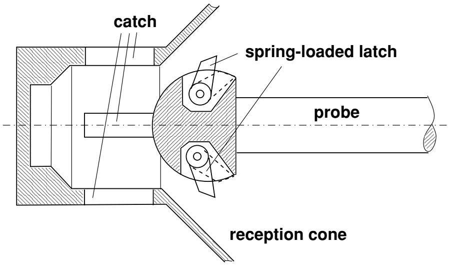

Figure 8.25. Central docking system: principle of capture latch.

Passive capture latch for peripheral systems Whereas the central docking system does not lend itself to a 'capture before first contact' strategy, the peripheral docking system can be designed in both ways. For passive capture latches, spring-loaded latches are typically arranged in the middle of each petal; these engage with corresponding catches between the petals on the opposite docking ring. Such latch–catch interfaces can be arranged on both chaser and target sides of the docking system (androgynous design), providing additional redundancy to the function (see figure 8.26). A special mechanism will be used for withdrawal of the capture latches if the two halves have to be separated for any reason during the docking process. The final alignment requirements, which have to be achieved for successful capture, are more critical for a peripheral system than for a central one. This is due to the design relations of a system, where all alignment and capture elements are arranged near the outer diameter. In particular, angular misalignments must be small to engage all capture latches. To achieve the alignment requirements, the shock attenuation system has to be sufficiently compliant. Friction forces due to the petals during mechanical guidance, and spring and friction forces of the capture latches, will be more critical for capture than in the other designs, because of the complex motion, after contact, of the multiple contact points and of the long lever arms at which these forces act w.r.t. the centre line. As a result, a relatively high contact velocity is required for successful capture. Also, in this type of docking system, additional boost along the chaser's longitudinal axis is usually applied to support capture.

Active capture latch for peripheral systems In contrast to the passive spring-loaded latch, latch engagement will in this case be operated by an electro-motor. The capture strategy to be applied will be 'capture before contact', in order to provide the maximum possible time available for the closure of the latches. It is obvious that this strategy leads to successful capture only if the approach velocity is small compared with the latch closure velocity. Closure of the capture latches has to be initiated immediately once all capture interfaces are within their according reception ranges. Proper capture conditions will either be detected by dedicated sensors, e.g. light-barrier sensors near the latches or petals, or will be reconstituted from the position and relative attitude measurements of the rendezvous sensor, if accurate enough. Requirements for final alignment at the

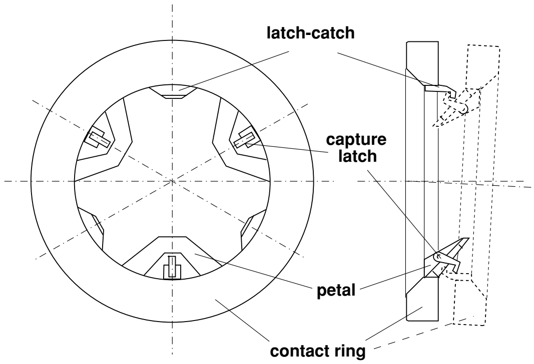

Figure 8.26. Peripheral docking system with passive capture latch.

instant of capture will be less demanding than for passive capture latches. This will make capture more reliable. However, larger misalignments at the entrance into the reception range, due to GNC performance, would have to be compensated for by relatively large dimensions of the capture latches.

An example of an active capture latch system is shown in figure 8.27. The design is an over-centre latch, which is self-locking in the closed position. The linkage is designed such that the trajectory of the latch tip after initiation travels, in a very short time (1–2 s), from the ready position to the capture position, at which the interfaces can no longer escape. The system includes a minimum of three capture latches, which are actuated individually. The second part of the latch trajectory serves the functions of retraction and alignment for structural connection. To keep the dimensions of the capture latch low, the combination of angular and lateral misalignments at a given docking ring diameter must not exceed a certain value. For a latch with the total dimension of $\approx$0.5 m, the typical longitudinal and lateral capture range is between 0.2 and 0.25 m. Assuming that lateral and angular misalignment share equally the reception range, the lateral misalignment must not exceed $\pm$0.1 m and the angular misalignment in pitch and yaw must not exceed $\pm$3 deg with a docking ring diameter of the order of 1.5 m. The acceptable angular misalignment on entering the reception range is further reduced by the approach velocity and rebound motion. The system was designed for a nominal approach velocity of 0.02 m/s and the acceptable angular misalignment was $\pm$1.5 deg.

Magnetic capture devices The capture device consists of a number of electro-magnets arranged on the circumference of the contact ring. The interface on the target vehicle consists of soft iron counterparts at places corresponding to those of the electro-magnets on the chaser side. When these interfaces are brought into close vicinity, they will attract each other, ensuring contact and attachment in an aligned state. The advantages of using electro-magnets as capture devices are that no mechanical capture latches are needed and that alignment occurs automatically. A problem with the application of magnetic

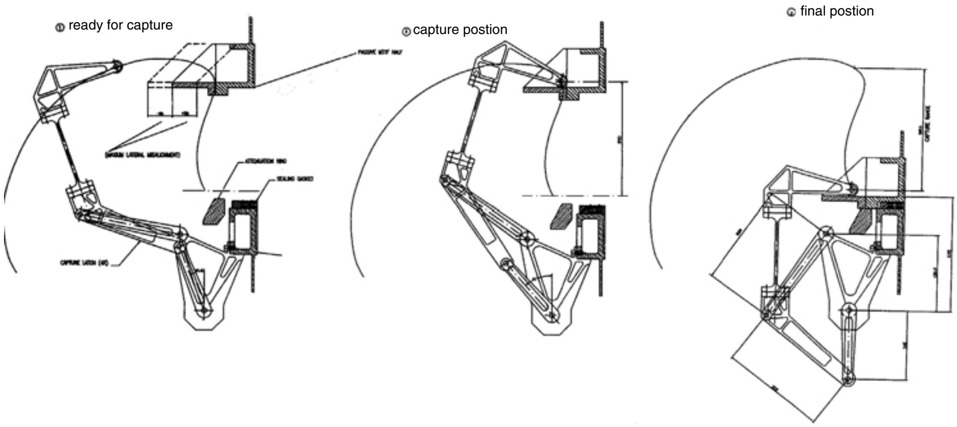

Figure 8.27. Peripheral docking system with active capture latch (courtesy ESA).

devices for docking is the force characteristic of magnets, which decreases by $1/r^2$ with the distance r. This means (a) that at larger distances the forces of the magnets may not be sufficient for capture, and (b) that at shorter distances, when the magnetic forces are large enough to initiate capture, the vehicles will accelerate toward each other, rather than decelerate, which is essential for smooth contact. This characteristic of magnets may be overcome either by actively controlling the magnet forces as a function of their distance, or by actively aligning the contact rings w.r.t. each other, and by engaging the electro-magnets only when the distance to their counterparts has become practically zero for all of them.

Capture mechanism for berthing (grappling/grasping) As already discussed above, there are two capture tasks in a berthing scenario: (a) to perform a first connection between the vehicles by a manipulator arm, and (b) once insertion into the berthing mechanism is achieved, to prepare for structural connection.

In order to be able to exploit the potential advantages of berthing, i.e. large envelope of position and relative attitude at capture, the capture system for the first connection must be able to cope with significant misalignments between the vehicles. The major part of these misalignments will be compensated for by appropriate articulation of the manipulator joints. As the arm is manually controlled, there will be residual misalignments, however. For this reason, the end-effector must have a sufficiently large reception range.

There are many types of end-effector designs developed for industrial and scientific applications. The design used for most berthing operations in space is the end-effector developed by the Canadian Space Agency (CSA) together with the manipulator arm for the US Space Shuttle (Ussher and Doetsch 1983). This design is now used also for the ISS. The principle of operation is shown in figure 8.28. The interface on the

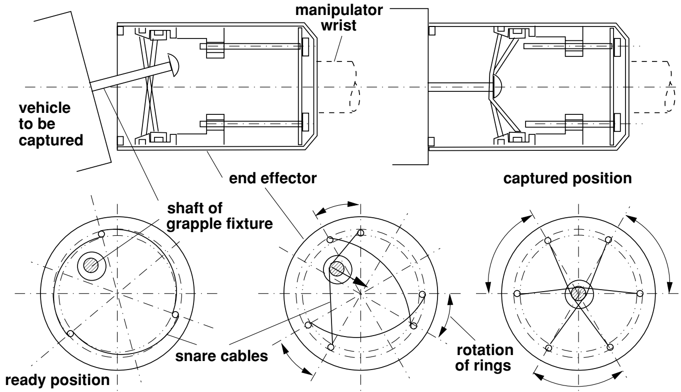

Figure 8.28. Manipulator end-effector and grapple fixture (developed by CSA).

vehicle to be captured consists of a rod (grapple fixture), which has a base structure for alignment and firm connection. The end-effector consists of a cylinder, which contains a mechanism with three snares. For a man-in-the-loop controlled capture, the operator of the manipulator steers the end-effector to follow the residual motion of the grapple fixture and to align the two interfaces with the aid of a visual target pattern, similar to the one shown in figure 6.23. When sufficiently aligned, the end-effector will be placed over the grapple rod and the snare mechanism activated. The snares will then close around the rod and prohibit escape, as shown in figure 8.28. During subsequent operation, the snares are further tightened and pulled in the direction of the wrist of the arm. This presses the end-effector cylinder against the base of the grapple fixture, providing a firm connection between the two.

The capture mechanism for insertion into a berthing mechanism, shown in figure 8.29, is the design for the Common Berthing Mechanism (CBS) developed by NASA for the Space Station. The design is an over-centre latch similar to the one shown in figure 8.27 for docking. The design criteria, however, are different. Whereas in docking the motion from the 'ready' position to the 'capture' position must be as fast as possible to prevent escape, such a requirement does not exist in this case, since the manipulator can hold the interfaces in position as long as necessary. Also, the misalignments at capture in a berthing mechanism will be comparatively small, as the manipulator arm can push the petal interfaces into each other, improving the preliminary alignment. The capture latch design will, therefore, be optimised for minimum size and mass, for small initial misalignments and for no time constraints. A spring is mounted between the first member of the linkage (the one with the hook) and the second member; this spring bends the upper member (hook) forward and provides the necessary flexibility in case of misalignment between the berthing interfaces. When all hooks are in contact with their corresponding catches on the opposite side, they will pull the two berthing rings together.

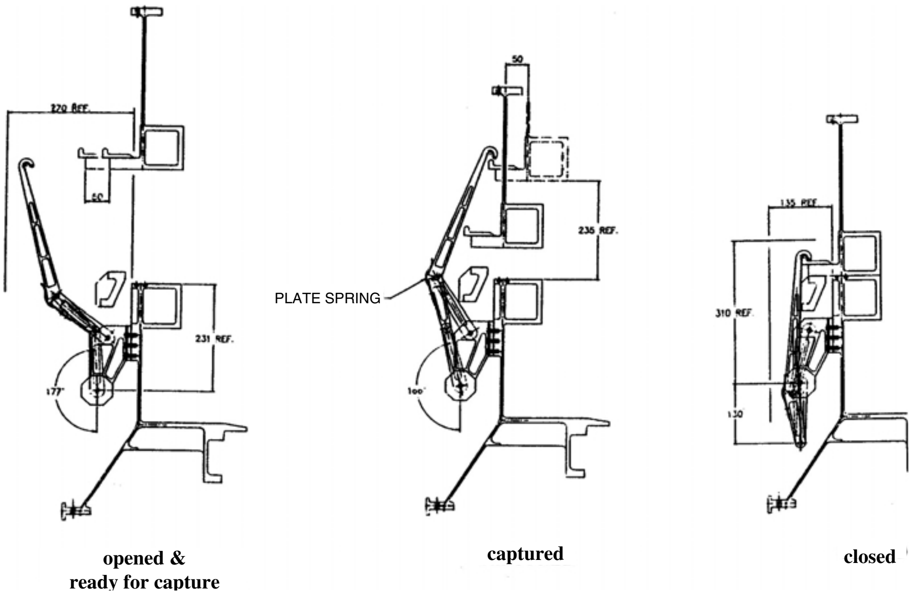

Figure 8.29. Capture latch of berthing mechanism (courtesy NASA).

8.3.6 The interface between the GNC and the mating system

As contact and capture dynamics are very closely related to the GNC performance, their interfaces will be addressed here before discussing structural connection and sealing issues and elements. In the previous sections of this chapter, we have already seen that the choice of functional principles and the detailed design of the elements for capture and shock attenuation depend on the lateral and angular displacements and on the translational and rotational velocities between the capture interfaces of chaser and target at the instant of contact or just prior to it ('capture before contact' strategy).

Generally, in the case of docking, to keep the impact, and therefore the size of the attenuation system, low, contact and lateral velocities and angular rates should be as low as possible. We have seen, however, that for the 'capture after contact' strategy, generally a minimum velocity is necessary to achieve mechanical guidance by the probe–cone or petal–petal interfaces and for actuation of the spring-loaded latches.

The requirements for berthing have been addressed already in section 5.3.1. The ideal conditions for capture by the manipulator would be zero relative translational and rotational rates; this situation is not possible, however, because of orbital dynamics and residual rates after switch-off of the reaction control system.

Performance requirements for the GNC system have already been addressed to a certain extent in chapters 6 and 7. In chapter 6, possible control strategies for docking (see figure 6.9) have been indicated, showing that it is necessary to control relative attitude in addition to lateral trajectory deviations, in order to achieve sufficiently small misalignments at docking. Further, the causes of control deviations have been addressed in section 6.2.3. In chapter 7, the requirements for sensor performance at docking have been derived from an assumed reception range of a docking mechanism, giving an allocation to control performance and to uncompensated target motion (see figure 7.3).

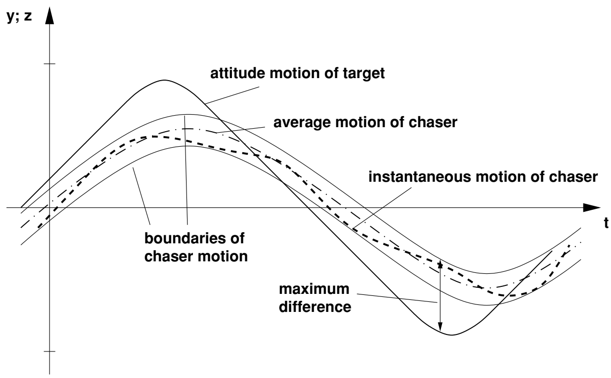

Figure 8.30. Motion of target and chaser at docking.

The effects on the reception requirements of the chaser GNC performance in pursuing the target motion will be investigated more closely in this section. The docking port of a vehicle is necessarily at a certain distance from the CoM. As a result, angular motions about the CoM of the vehicle translate into lateral motions of the docking port. The solid line in figure 8.30 is the lateral motion of the target docking port resulting from a typical two-sided limit cycle (saw-tooth) attitude motion. The rounded-off corners are due to the available thrust level and the inertia of the target spacecraft. Due to the filtering and control processes (see chapter 6), the chaser will follow the target motion with a certain delay. Further, its trajectory and relative attitude will deviate somewhat from the target motion due to sensor performance and the thruster selection process. The chaser motion may also exhibit lower amplitude, due to (e.g.) bandwidth limitations of the chaser GNC chain. As a result, the lateral motion of a chaser following the target motion may resemble the thick dashed curve in figure 8.30, labelled ‘instantaneous motion of chaser’. The deviations are of a random nature and can be described by an average motion, with margins on both sides, indicated as ‘boundaries of the chaser motion’ in the figure. The reception range of the docking mechanism must be larger than the maximum possible difference between the lateral motion of the target docking interface and that of the chaser. The simplified diagram in figure 8.30 shows of course only one of the six degrees of freedom to be controlled.

In order to avoid unwanted reactions by the GNC system on the contact dynamics, the reaction control system (thrusters) of the chaser will have to be inhibited prior to, or at, contact. This can be initiated either upon detection of the docking interfaces entering into their mutual reception range, at a certain distance measured by the rendezvous sensor, or upon detection of first contact. The navigation, guidance and control functions will have to continue operating, in order to facilitate immediate retreat if necessary, e.g. if the capture fails. For the auxiliary thrust that is necessary to support capture, which has been mentioned above, thrusters providing force components in the direction of the docking axis will be initiated upon detection of contact by an independent command string outside the GNC.

The conclusion of all the discussions so far is that the requirements concerning reception, shock attenuation and capture are interdependent with the GNC performance requirements. This means that a balance has to be found between the capabilities of the GNC and docking systems.

- High approach velocities, lateral and angular rates and misalignments at contact require large reception ranges and attenuation systems with large excursions. Capture can be performed only after contact, and the capture function can best be implemented by passive spring-loaded latches. From the dynamics point of view, the best docking system for high velocities, angular rates and misalignments is central docking, which offers large lateral and angular reception ranges and relative simple design implementation possibilities for the shock attenuation system, capable of coping with large impact shocks. Peripheral systems offer a better clearance of the transfer tunnel at the expense of significantly increased design complexity and potentially reduced reception capability.

- High GNC performance, with low approach velocities and misalignments, allows the application of a 'capture before contact' strategy. This involves the application of active capture latches, which do not require a certain residual relative velocity between the vehicles for successful capture. The reduced shock attenuation requirements allow for the application of small and simple damper devices.

- Capture by a manipulator for berthing does not require high positioning and angular alignment performance by the chaser GNC, but rather nominally zero velocities and angular rates. This requires also a relatively high GNC performance (see also sections 5.3.1 and 7.1.1).

8.4 Elements for final connection

The residual functions of docking and berthing mechanisms are the structural latches, seals, utility connections, and the sensor and detector functions. Only the structural latches and seals will be discussed in this section for completeness of understanding of the docking/berthing mechanism functions. These functions are fully independent of the flight (GNC) and contact dynamics (reception, shock attenuation, capture) complex, and can also be considered in the verification process (see chapter 10) completely independently. The subject of utility connections is outside the scope of this book, as additional technical fields unconnected with the understanding of rendezvous and docking in space would have to be covered. The design principles used for these functions are basically no different from those used for automatic connection/disconnection mechanisms on ground.

8.4.1 Structural latches

The tasks of the structural latches are as follows:

(1) To provide the necessary strength and stiffness of the connection, necessary to transmit internal and external loads caused by, e.g., crew and payload motion, thruster firings, EVA, manipulator activities, further docking and berthing operations, and as required for attitude control of the joint vehicle.

(2) To provide the necessary compression force at all points of the circumference of the docking or berthing ring for optimum functioning of the seals.

The second task, which is required only in manned missions, puts the highest demand on the structural latches. If the inner pressure is equivalent to that of the normal Earth atmosphere at sea level, i.e. $p = 9.81$ N/cm^2, the total force to be carried by the structural latches is $f_\mathrm{p} = pd^2 \cdot \pi/4$. For example,

- at a diameter of the sealing ring of 1 m, $f_\mathrm{p} = 77\,048$ N;
- at a diameter of the sealing ring of 1.5 m, $f_\mathrm{p} = 172\,764$ N.

The actual pressure in a space station may be reduced to 50–60% of the sea level value, which has advantages w.r.t the structural loads, the consumable budget and the EVA activities. In addition to the pressure force, the latches have to provide the compression force for the seals, ensuring their gas tightness, plus a safety margin. The resulting force level is orders of magnitude higher than all the other loads, listed under point (1) above, which makes it the major design driver for the structural latches.

The quadratic increase of the pressure force with the diameter of the pressurised area eventually puts constraints on the design of structural latch assembly. To carry the pressure load at a given seal diameter, a certain number of latches may be required. Increasing the seal diameter by a factor of n would mean that the number of latches of the same design would have to be increased by a factor of n^2 to carry the increased pressure load. As the circumference of the ring has increased only linearly, this may eventually cause accommodation problems for the latches and may, as a result, require the use of latches with higher load carrying capability.

Another parameter which changes with the increase of the sealing ring diameter, and which affects the effectiveness of the sealing, is the stiffness of the structure. If all dimensions are increased linearly, the stiffness also increases linearly, whereas the pressure forces increase quadratically. As a result, the bending of the structure will increase, which in turn requires a larger number of connection points to keep a sufficient and equally high pre-load on the seals along the circumference.

In summary, a significant increase in the tunnel diameter will lead to a requirement for both increased load carrying capability and a higher number of latches.

Examples

- *Soyuz/Progress central probe–drogue docking system.* The tunnel diameter is 0.8 m and the diameter of the sealing rings is approximately 0.95 m. The mechanism has eight structural latches of the hook type (plus eight redundant ones from the other half of the system).

- *APDS (androgynous peripheral docking system).* The sealing ring diameter is approximately 1.2 m. The mechanism has 12 structural latches of the hook type (plus 12 redundant ones from the other half of the system).

- *Hermes–Columbus docking system.* The diameter of the sealing rings is 1.6 m. The mechanism has 12 latches of the screw type (on the active side only).

- *ISS common berthing system.* The diameter of the sealing rings is about 2 m. The mechanism has 16 latches of the screw type (on the active side only).

There are two basic design principles used for the structural latches, i.e. the ‘hook’ type (figure 8.31) and the ‘screw’ type (figure 8.32). The hook type latch has been developed for the Soyuz/Progress and APDS docking systems. The trajectory of the hook latch is generated by a simple eccentric cam. The design includes at each latch location an active and a fixed passive hook. In the Soyuz/Progress system, all active hooks of one side are driven together by one actuator via a steel cable system. In the APDS system, because of the increased pressure forces and number of latches, there are two actuators which operate, via steel cables, six active latches each. The force transmitted in each string of steel cable must have a very high margin to ensure reliable operation under all conditions. An advantage of the hook system is that the ‘fixed’ hook can be designed such that it can be released if necessary (e.g. by pyrotechnics and springs). If a double hook arrangement is used, as in the Soyuz/Progress central docking system and in the APDS (principle shown in figure 8.31), a firm structural connection can be achieved also by actuating the latch system of the other side, which provides full redundancy to the system.

With increasing diameter of the sealed area, the forces become so high that eventually a reliable operation of the hook latch design becomes problematic. For this reason, for mating systems with a very large diameter of the sealed area, such as the common berthing system of the ISS or the Hermes–Columbus docking system, the screw type of structural latch with individual actuators has been chosen. With screw type latches, higher pre-loads can be achieved at a given torque delivered by the actuator.

A further advantage of the screw latch with individual actuator is the possibility of controlling the pre-load individually at each latch, which is not so in the case of a hook

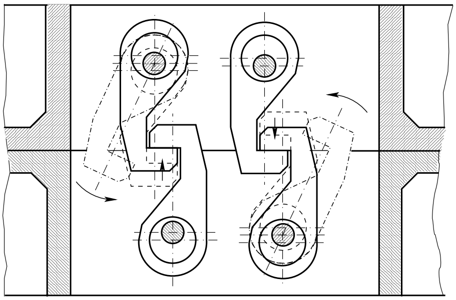

Figure 8.31. Structural latches, hook type.

latch arrangement. This advantage has to be paid for, however, by the increased expenditure in electrical circuitry and motors and by the increased amount of single-point failures. To provide redundancy and to mitigate single-point failure possibilities, screw latches must be capable of being operated from two sides, i.e. the bolt and nut must be capable of being operated independently.

For all structural connections which are not intended to be permanent, it is extremely important that they can be opened again. For separation and departure, if there are no capture latches, holding the two docking rings in position, the structural latches must open at the same time. In contrast to the hook latch arrangement, which is operated jointly by a steel cable, this condition will be more difficult to achieve with a large number of individually operated latches. For this reason, with the screw type of latch, it will be safer to re-engage first the capture latches, then to de-pressurise and open the structural latches, and eventually open the capture latches for separation. For individually operated capture latches, the problem of a single latch failure still exists. The immediate repercussions can be limited if, prior to capture latch opening, the attenuation system is expanded and does not exert spring forces on the latches. Opening of a failed latch can then be forced by a pyrotechnic release mechanism.

As the above-described redundancy by separate bolt and nut operation cannot cover all possible failures, e.g. cold-welding between the flanks in the thread, additional possibilities for opening of the latch have to be implemented. This can be done, e.g., by bolt-cutting pyrotechnic devices. However, as the expense in terms of design complexity may be relatively large, and the amount and size of the pyrotechnics may be unwanted because of safety-criticality, the screw latches are usually placed inside the sealing rings, so that they can be accessed by IVA operation. The solution would then be to remove and replace the complete latch manually, providing temporarily the pre-load by auxiliary clamps attached to the flanges of the docking/berthing rings. In docking mechanisms with smaller tunnel diameter, such as the Soyuz/Progress and APDS, structural latches and other devices which cannot be removed after connection are preferably arranged outside the sealing ring, to maximise the available cross-section for transfer. Since EVA will be required, this of course increases the complexity of such manual operations.

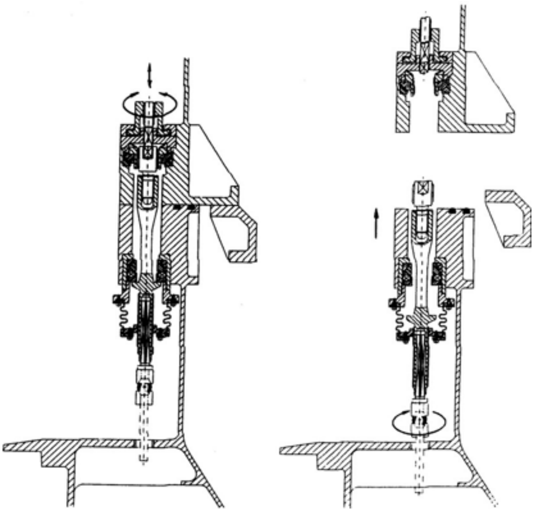

Figure 8.32. Structural latches, screw type (courtesy ESA).

A typical design of a screw type structural latch, which was developed for the Hermes–Columbus docking system, is shown in figure 8.32. In this case, the latches are mounted inside the seals. Both bolts and nuts are mounted in spherical bearings to compensate for misalignments. For contingency separation, the bolt can be operated from the nut side by rotation of a shaft in the centre of the nut assembly; this has a square cross section at the tip and can be moved downwards to fit into a square hole at the tip of the bolt.

8.4.2 Seals

To keep the forces which have to be applied by the latches to compress the seals low, the seals should be arranged at the smallest diameter possible. As we have seen, however, there may be overruling considerations, i.e. access to essential devices from the inside, which move the seals to the outer diameter of the interface ring (see figure 8.32). For redundancy reasons, generally two concentric seal rings are applied. Pressure measurements can be performed in the volume between these two rings, and these provide an indication of the leak-tightness of the seals (see figure 8.33). If the pressure of the volume is equal to the inner pressure, the inner ring is leaking. If the pressure is equal to the outer pressure, there are theoretically two possibilities: (a) the outer ring is leaking or (b) both rings are absolutely airtight. In case (b), after structural connection and subsequent pressurisation, the volume would still have the outside pressure. It would be possible to implement small diameter ducts, with valves to both inside and outside, which apply either the inside pressure or a vacuum and to determine the nature of a leakage from the pressure development.

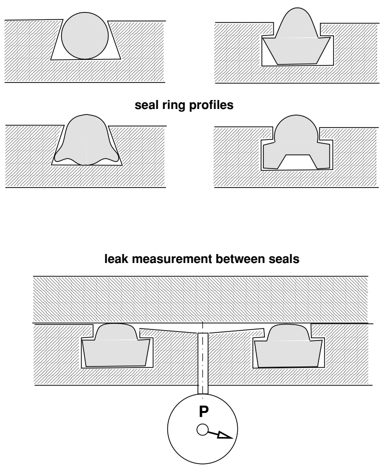

Figure 8.33. Seal ring profiles and leak measurement.

Seals must be sufficiently flexible so as to comply with the form of their interfaces, even on the scale of surface roughness; i.e. on one side with the groove in which they are held and with the interface surface on the opposite side. On ground, metals and elastomers are used as sealing materials, together with low-outgassing greases. In space, in docking/berthing applications, however, grease and metallic seals may not be used for a number of reasons, the most important of which are:

- grease: high adhesion force, causing a problem at separation; lack of chemical stability under conditions of radiation and atomic oxygen;
- metal seal: very high compression forces necessary to achieve air tightness; plastic deformation of metal allows for only one operation.

This leaves synthetic elastomer materials as the only possibility of providing the mechanical properties for docking/berthing seals. Unfortunately, these materials lose their properties during long term exposure to space conditions and, for this reason, missions have to be arranged such that seals are not exposed to orbital environments for more than a couple of days. This has the following consequences:

- docking/berthing interfaces on the outside of a space station must not carry seals;
- seals for docking/berthing connections must be located on the servicing vehicle side, which will be in orbit for only a few days up to a few weeks until it is connected to the target;
- at disassembly and re-assembly of modules for reconfiguration of an orbital complex, all seals must be covered again, either by the mating interface of its opposite module or by a hatch.

It is hoped that, in the future, materials and seal designs will be developed which are capable of long term exposure to space conditions. Until such seals become available, it is obvious that the idea of androgyny of docking/berthing interfaces cannot be fully implemented and the benefits of these designs cannot be exploited.

There are many types of seal cross sections used in applications on ground. A few examples are shown in figure 8.33. To be used in mating interfaces of space vehicles, the profiles of the seals and of their corresponding grooves must fulfil two requirements:

- The seal ring in its groove must be firmly attached such that it is capable of withstanding launch vibrations and accelerations, as well as possible lateral motions during closure and alignment for structural connection. Adhesion forces during separation must not lead to extraction of the seal from the groove.
- A maximum of the seal surface must press against the opposite mating ring and the groove walls at maximum compression, i.e. when metal to metal contact is reached between the interface rings.

Because of the second requirement, the seal profile must not only protrude from its interface ring, but the difference between seal and groove cross sections must be such that the groove is almost completely filled when maximum compression is reached. As the seal material is flexible but incompressible, seal and groove profiles have to be carefully matched, i.e. there must remain a very small amount of freedom when metal to metal contact is reached.

After compression of the seals, and in particular if the seals are attached for a certain time, there will be adhesion between the seal and the opposite wall, requiring a certain force to achieve separation. Even larger forces may be required to separate power and fluid connectors, if they do not have their own separation devices. For this reason some docking mechanism designs include a number of ‘pushers’ around the docking ring, which apply the necessary forces. These are passive spring-loaded rods, which have been compressed during structural latching and are released at separation. In other designs, the contact ring, which is connected to the shock attenuator devices, provides the separation force. In berthing, the vehicle or module to be removed is separated by means of the manipulator arm. The ‘pushers’ may be used additionally to provide the initial ΔV to the departing vehicle, so that the thrusters need to be operated only when a distance of a couple of metres has been reached.