N89-12606

CONTROL OF THE INDUCED MICROGRAVITY ENVIRONMENT OF THE MAN TENDED FREE FLYER (MTFF)

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ABSTRACT

The MTFF one element of the European COLUMBUS program is an unmanned free-flying platform. It will mainly be utilized for long-duration science investigations and automatic processing, both requiring long periods of nearly zero-g conditions. At spacecraft/payload interface the sum of disturbances shall not exceed spectral 10E-6 g below 0.1 Hz and 10E-4 g above 100 Hz.

Based on past experience main sources of induced disturbances are expected to come from turbulent flow of air and fluid loops, imbalances of gyroscopes and reaction wheels.

The excitations are amplified by local and global structural resonances including low frequency modes of spacecraft flexible appendages and fuel sloshing and result in harmful accelerations of the sensitive payload. At the present stage worst case assessments basing on analyses and test results indicate that great effort and expense are necessary to meet the strong microgravity requirement.

With ongoing project realization especially during design and development phases microgravity control activities will become utmost significant for the realization of a minimized residual acceleration environment. They include design optimization and its verification by simulation and test, structural transmissibility measurements with the structural and the integrated engineering model, the creation of a qualified disturbance superposition model for the prediction of payload responses and in last consequence the implementation of passive and active anti-vibration mounts.

In future the performance of Microgravity Environment Compatibility (MEC) Tests on system, element and subsystem level will get high priority. Their results will constitute the basis for reliable predictions of the expected induced microgravity environment during the on-orbit operational phases.

INTRODUCTION

The term microgravity is used to describe the physical environment in an orbiting spacecraft (S/C). The most obvious feature of this environment is extremely low gravity which is not obtainable on earth for long periods.

The MTFF is an unmanned free flying laboratory for the automatic performance of processes and experiments in the field of solidification physics, physical chemistry, liquid physics, biology and biotechnology under low gravity conditions during a period of 180 days.

The present MTFF design assumes that about ten experiment dedicated double racks or twenty single racks can be accommodated and that the equivalent of ten further double racks is available for subsystem and experiment stowage. The orbital laboratory and main system data are shown on Figure 1.

The MTFF consists of a two segment Pressurized Module (PM2) providing the pressurized laboratory environment for research and application and its own Resource Module (RM) providing basic resources and services such as electrical power, heat rejection, guidance and navigation, attitude stabilization and control, communication and data transmission, orbital transfer and rendezvouz and docking capabilities. Exploded views of PM2 and RM elements are given with Figures 2 and 3.

The MTFF will be serviced by astronauts at intervalls of 180 days. It has been designed for a lifetime of 30 years.

Two main kinds of disturbance sources contributing to the low g environment at the spacecraft/payload interface have to be distinguished :

- o The natural environment acts on the surface and center of gravity of the MTFF, results in position independant accelerations inside the MTFF and exhibits slow time variations along the spacecraft orbit. Natural disturbances sources are :
  - drag forces due to ambient ionospheric medium, especially aerodynamic drag
  - solar radiation pressure
  - earth gravity gradient
  - momentum transfer from micrometeorid fluxes
  - self-gravitational field due to S/C internal mass distribution
- o Induced disturbances are generated by on-board equipment and subsystems. Examples are given with :
  - reaction wheels and gyroscopes of GNC subsystem (S/S)
  - fans, pumps, centrifuges, air and fluid loops of ECLS- and TCS-S/S
  - residual torque of GNC attitude control in combination with the excitation of low frequency dynamics of the S/C flexible appendages (solarr arrays, antenna and fuel sloshing).

For response predictions at P/L-S/C interfaces the disturbance force excitation functions have been multiplied with an empirically found vibration transfer function which has been derived from measurements with typical S/C lightweight structures.

In this paper main considerations are given to induced disturbances occuring during MTFF operational phases. From technical view it deals with disturbance source identification, vibration transmission, response predictions and their verification. Programatic aspects are covered by requirement definitions and the presentation of the project microgravity control plan.

MICROGRAVITY REQUIREMENT DEFINITION

At the present stage the MTFF system microgravity requirement is defined as follows :

- The quasi-static steady state acceleration of the MTFF in its operational orbit shall be not greater than 10E-6 g.
- Distubances created by and within the MTFF, by its equipment, when added to the quasi-static level above shall not cause accelerations at the payload interface greater than :

    10E-6 g below 1 Hz
    10E-4 g above 100 Hz
    log-linear interpolation between 1Hz and 100 Hz

Payload interface acceleration must be understood as sum of natural and induced disturbances. Payload disturbance contributions are not included.

The requirement breakdown and microgravity budget allocation on element (PM2, RM) and subsystem level has been performed with respect to SPACELAB experience, equipment and subsystem similarity assessments and study results. The allocated microgravity budgets are given with Table 1.

The requirements define the resultant limit amplitude of the three translatory acceleration components at the microgravity payload/spacecraft interfaces. Below 0.1 Hz the system requirement breakdown has been performed linear, above 0.1 Hz on power basis (root-sum-square).

The definitions given above must be considered as preliminary, future corrections can be expected. Presently it is under discussion to compare equipment, subsystem and element disturbances against rms-values of third octave bands at their center frequency.

With ongoing design and development activities the results of equipment and assembly development tests may show the necessity of a microgravity budget reallocation mainly to be performed on equipment and subsystem level.

IDENTIFICATION OF DISTURBANCE SOURCES

PM2 and RM equipment and subsystems are expected to be main contributors to the induced microgravity environment on board the MTFF. They are mounted in the PM2 subfloor area and in RM Orbit Replacable Units (ORU's). A detailed list of vibration and noise generating equipment and their location is given with Tables 2, 3 and 4. The Tables must be seen in connection with Table 5 qualifying the excitation characteristics.

The drives of solar arrays and antenna pointing mechanism will be locked and thrusters not be activated during the MTFF operational phases.

The residual torques resulting from natural environment disturbance torque compensation in combination with low frequency S/C dynamics must be considered as contribution from RM GNC subsystem.

Earth ambient conditions within the PM2 element will be provided by the ECLS only during man tended servicing phases. It can be expected that the related equipment will not operate on full level condition during the MTFF operational phases.

Characteristics and original causes of structure-borne vibration mechanism are presented by Table 5. This kind of vibration will be transmitted directly via the structure from disturbance source location to the sensitive payload.

Additionally the coupling of structure-borne vibrations with air-borne sound must be be considered. Surfaces of cold plates, heat exchangers, ducts and S/S assembly housings radiate air-borne sound into subfloor, rack and cabin volume received by rack-, drawer surfaces and P/L casings. It is transformed into structure borne-vibrations and must be added to the structurally transmitted vibrations. Refined vibro-acoustic analyses to be performed in future will give reliable data on their parts of contribution.

STRUCTURAL TRANSMISSIBILITY FUNCTION

The allocated microgravity budgets refer to S/C-P/L interfaces. The vibration transfer function allows the prediction of payload responses due to force excitation at source location. It is defined in terms of g's per Newton [g/N] and represents the reciproke value of the effective mass participating at vibrations. Rotational rigid body responses have to be considered at the utmost radius of possible P/L location on board the MTFF.

The structural dynamic vibration characteristics of typical S/C lightweight structures have been determined by measurements with SPACELAB paletts and SPAS-01 satellite under variation of excitation/receiver location and local mass loading. Although both S/C's are different in their structural design similar vibration transmission characteristics have been found. A detailed description is given by Reference [1].

The envelope of these measurements under assumption of worst case constraints is presented by Figure 4. It is expected that this function gives a well description of structural transmission behaviour of typical S/C lightweight structures. Consequently the function has been used for first response predictions during early project phases.

Vibration amplification at eigenfrequencies of S/C flexible appendages (solar array, antennas) and of fuel sloshing are not covered by the transfer function. These effects will be controlled together with the natural environmental disturbance torques by the GNC S/S momentum management.

Future control activities must include verification and adaption to real MTFF transmissibility by numerical analyses and in the higher frequency range by measurements taken from Engineering and Structural Models . At source location the S/C mechanical impedances have to be determined for the coupling of equipment and assembly test results with the measured system vibration transfer characteristics.

RESPONSE PREDICTION AT S/C - P/L INTERFACE

Acceleration responses to identified potential disturbing equipment have been assessed by determination of the force excitation functions and its multiplication with the spacecraft vibration transfer function. Assumptions and equipment characteristics being used for analyses are given in the following.

For four reaction wheels (RW's) static and dynamic imbalances and rotor axial bearing force have been superposed under consideration of :

rotating mass of RW : $m = 20$ kg
heigh of RW : $h = 0.2$ m
diameter of RW : $d = 0.5$ m
max. rotational speed : $n = 4000$ rpm
balance quality grade : $Q = 6.3$ mm/sec (rms)
axial bearing forces base on measurements results.

The results of Freon and water fluid loop vibrations are derived from measurements. The test set-up consisted of :

1 pump package, 1 interloop heat exchanger, 1 standard coldplate, 1 throttle line and diverse flexible and hard lines with bends.

loop medium	Freon	Water
flow rate	1400 kg/h	235 kg/h
total pressure drop	1.73 bar	0.95 bar
pump type	SL Freon 21 pump, 2-stage, centrifugal	REUSSER, 1-stage, centrifugal
no. of impeller blades	12	6
no. of diffuser blades	9	-
power	300 W	34 W
loop fundamental freq.	180 Hz	130 Hz

Following data have been used for high data rate recorder (HDRR) disturbance force assessment :

tape diameter : $d = 0.38$ m
rotating mass : $m = 5$ kg
fast rewind speed : $u = 6$ m/sec
acceleration time : $t = 1$ sec
shape of excitation : rectangular force pulse
analysis bandwith of frequency transformation : 0.5 Hz

The stiction-friction effects at structural bearings by sudden stress compensation due to thermal extension/contraction have been assessed with :

mean strain : 50 * 10E-6
modulus of elasticity : 70 * 10E3 N/mm2
cross section area : 940 mm2
shock duration : t = 1 sec
shape of excitation : rectangular force pulse
analysis bandwith of frequency transformation : 0.5 Hz

It is assumed that stick-slip will act as inner force/moment on the S/C and thus not induce any acceleration of the rigid body. A detailed description of this phenomena is given with Reference [2].

Gyroscope forcing functions base on the superposition of following forces and torques measurements :

force parallel to spin axis
force orthogonal to spin axis
torque around axis orthogonal to spin axis
wheel frequency : 400 Hz

Cabin and avionic fan induced accelerations at payload racks base on measurements performed in the SPACELAB Engineering Model.

Responses to acoustic excitation are derived from SPACELAB analysis and test data due to its similarity to the COLUMBUS pressurized module design.

The computed acceleration response amplitudes to excitations from equipment as listed above are presented graphically in terms of g's by Figure 5.

The responses to RW and gyroscope vibrations are given by the envelopes over all possible operating steady states. The equipment itself have been assumed to behave as rigid bodies. Structural resonances have not been considered.

The assessed disturbance level due to shock excitation shall only give an impression about the order of magnitude since the real values are strongly depending on time duration and shape of excitation pulse.

Many disturbances may occur at the same time. But their superposition will become very complex due to different types of excitation and the time dependant variation of their magnitudes and directions.

The checkered area on Figure 5 shows expected response level reduction by design modifications like for example the implementation of active or passive anti-vibration-mounts or refined manufacturing tolerances as the improvement of balance quality grades of rotors.

VERIFICATION BY ANALYSIS AND TEST

Based on the allocated budgets, verification of the induced microgravity environment has to be performed on system, element and subsystem level by analysis or test, and where appropriate in a combination of both. An overview on methods for the verification of induced and natural microgravity disturbances is given in the following.

ANALYSIS OF INDUCED DISTURBANCES

The evaluation of induced disturbances by similarity assessments shall be used if calculations by means of simplified mathematical models during design definition and early development phase are impossible due to lack of detailed data. The article should be similar or identical in design, manufacturing process, quality and set-up (as integrated system) to another article that has been previously certified to equivalent or more stringent criteria.

Similarity assessments should also substitute most thorough analyses if it can be expected that time and cost effort are unproportionally high related to the accuracy of the expected results.

The analyses of equipment and subsystem disturbances have to show the influence on S/C rigid body motions and by application of the S/C transfer function on payload responses in the higher frequency range.

Realistic safety margins have to be considered by the analyses in order to facilitate the implementation of subsequent test results.

The analytical treatment of low frequency structural dynamics should be covered by the GNC mathematical model and its numerical simulation.

ANALYSIS OF NATURAL DISTURBANCES

The verification of the MTFF natural microgravity environment shall be performed by analysis and computer simulation, because tests can not applied to drag, gravity gradient and S/C low frequency dynamics investigations.

MEASUREMENTS OF INDUCED DISTURBANCES

Where other verification methods do not provide reasonable assurance that the candidate design or procedure is adequate to meet the microgravity requirement tests and measurements taken from operational equipment and the integrated system will form a basis for verification of the higher frequency microgravity environment.

Development tests shall be performed to verify the design approach, indicate critical areas where design improvement is required, assure compliance with design requirements, confirm analytical methods or generate essential design data.

In general, subsystems are tested on assembly and equipment level. It will be nearly impossible to mock-up completely integrated subsystems. The test article will be attached to a reference structure with a dynamically free-free and low frequency suspension. Test outputs are equipment interface forces and mechanical impedances to be combined analytically with the corresponding local S/C impedance and transfer function in order to derive its contribution to the induced microgravity requirement.

Development tests on element and system level with the Engineering and Structural Model shall determine structural vibration transmission characteristics, the dependency of structure borne vibrations from acoustic excitation and local S/C impedances for correlation with equipment test data.

Final PM2 and RM element verification is planned to be performed on system level in order to have realistic boundary conditions for each element.

Final system verification of the higher frequency contribution is provided by measurements taken of the fully equipped flight unit. Subsystems shall operate according to timeline.

It must be noted that ground tests will always be influenced by earth gravity and athmospheric pressure. Therefore on orbit verification may be foreseen for the support of payload performance evaluation during and after flight.

MICROGRAVITY QUALIFICATION APPROACH

Basis of the overall microgravity approach of induced disturbances are equipment and assembly development- and final verification tests. At the beginning of the design phase much effort should be spent to equipment and assembly development test preparation and performance. At early time necessary design modifications and microgravity budget reallocations could be recognized and implemented into overall approach.

The superposition of equipment and assembly test results will yield expected S/S disturbances. The superposition of S/S analyses results in expected element disturbances. Thus the quality of S/S, element and system analyses directly depends on the quality of equipment and assembly tests.

In parallel spacecraft vibration transfer characteristics have to be determined by early measurements with element Engineering and Structural Models.

PROJECT CONTROL PLAN

An overall control flow diagram given with Figure 6 shows the allocation of tasks and responsibilities to MTFF project contractors on system, element, subsystem and equipment level. The contractors shown on the Figure are representative for the remaining contractors. The project can be subdivided into one system responsible, two element contractors (PM2, RM), seven PM2-S/S contractors, nine RM-S/S contractors and one common subsystem contractor. Main tasks to be performed on each project level are :

- requirement definition and breakdown into subordinated requirement
- performance of disturbance analyses and tests
- proposals for and decisions about budget reallocation and design modifications
- preparation and performance of development and final verification tests
- report about analyses and test results to customer
- review of subcontractor tasks, review of analyses and tests and superposition of results to be delivered by subcontractors

SUMMARY AND CONCLUSIONS

Induced disturbance sources have been identified on board the MTFF and are shown with Table 2, 3 and 4. Vibration responses at sensitive payload/spacecraft interfaces have been predicted by the application of an empirically found spacecraft dynamic transfer function which is given with Figure 4. Vibrations from fluid loops (Freon, water) and of reaction wheels are assessed to be main contributors to the induced microgravity environment. The expected payload acceleration response amplitudes presented by Figure 5 are more than hundred times higher than the admissible values given by the MTFF system requirement, not considering the structural stiction-friction effects which could be avoided by appropriate design in any case. Real responses will be significantly lower because the derivation of excitation and transmission functions base on worst case assumptions.

The results indicate that future activities must spent much effort mainly on equipment design improvements and the implementation of vibration reduction means along the disturbance transmission path.

The activities must be accompanied by early equipment and assembly development tests and transmissibility measurements with the integrated spacecraft engineering and structural models in order to improve the accuracy of payload response predictions.

Table 1 : System, Element and Subsystem Allocated Microgravity Budgets (Payload Contributions not included)

ACCELERATION LIMIT LEVEL AT S/C-P/L I/F [g]	Frequency Range :			
	$f < 0.1$ Hz	$f > 0.1$ Hz $f < 1$ Hz	$f > 1$ Hz $f < 100$ Hz	$f > 100$ Hz $f < 200$ Hz
System Requirement :				
MTFF Overall Disturbances	10E-6	10E-6	f 10E-6	10E-4
MTFF Natural Disturbances	8 10E-7	7 10E-7	0	0
Element Requirement :				
PM2 Induced Disturbances	10E-7	5 10E-7	f 7 10E-7	7 10E-5
RM Induced Disturbances	10E-7	5 10E-7	f 7 10E-7	7 10E-5
Subsystem Requirement :				
PM2-ECLS	4 10E-7	3.2 10E-7	f 4.5 10E-7	4.5 10E-5
PM2-TCS	4 10E-7	3.2 10E-7	f 4.5 10E-7	4.5 10E-5
PM2-DMS	10E-7	1.6 10E-6	f 2.2 10E-7	2.2 10E-5
PM2-resid. S/S	10E-7	1.6 10E-6	f 2.2 10E-7	2.2 10E-5
RM-GNC	TBD	TBD	TBD	TBD
RM-TCS	4 10E-7	3.2 10E-7	f 4.5 10E-7	4.5 10E-5
RM-resid. S/S	TBD	TBD	TBD	TBD
vertical Requ. breakdown	linear	quadratic		

Table 2 : PM2 Induced Microgravity Disturbances Sources

SUBSYSTEM	EQUIPMENT	LOCATION	CHARACTERISTICS (see Table 5)
ECLSS-Cabin Air Loop	fan assembly	subfloor (SF)	1, 2, 3, 9, 13
	condensing heat exchanger (CHX)	SF	5, 7, 9, 10
	outlet diffusers	cabin (C)	9
	ducts, bends	SF, C	9
	valves, restrictors	SF	8, 9
	CHX bypass valve actuator motor	SF	1, 2, 3
ECLSS-Humidity Control	cond. separat. (centrifuge)	SF	1, 2, 3, 12
ECLSS-CO2-Control	CO2 control assembly	SF	1, 2, 3, 9
ECLSS-Avionic and Experim. Air Cooling	fan assembly	SF	1, 2, 3, 9, 13
	heat exchanger	SF	5, 7, 9, 10
	rack inlet diffuser	rack (R)	9
	ducts, bends	overhead (O)	9
	shut-off-valves	R	8, 9
ECLSS-Atmosph. Pressure Control	control-, relief-, exp. vent. valves	SF, C	8, 9
ECLSS-Fire Detect. and Suppress.	smoke detectors	SF, R	9

Table 3 : PM2 Induced Microgravity Disturbances Sources

SUBSYSTEM	EQUIPMENT	LOCATION	CHARACTERISTICS (see Table 5)
TCS water loop	pump assembly	SF	1, 2, 3, 5, 11
	valves	SF	5, 7, 8, 10
	cold plates	R	5, 7, 10
	tubing (flex/ hard line)	SF, C, R	5, 7, 10
STRUCTURE	bearings (joints, guides) bearing elements	module PM2-RM I/F	4, 14
EPS	DC/DC converter	SF	1
	relays	R	8, 12
	AC/DC inverter	R	1
DMS	mass memory (winch. drives)	R	1, 2, 3, 8, 12
	optical disk	R	1, 2, 3, 8, 12
	high data rate recorder	R	1, 2, 3, 12
COMMS	video tape recorder	C	1, 2, 3, 12
	video cameras	3 internal 2 external	1, 2, 3, 12

Table 4 : RM Induced Microgravity Disturbances Sources

SUBSYSTEM	EQUIPMENT	LOCATION	CHARACTERISTICS (see Table 5)
TCS-freon loop	pump assembly	ORU	1, 2, 3, 5, 11
	interloop heat exchanger	main body MB	5, 7, 10
	valves	ORU, MB	5, 7, 10
	tubing (hard/flex lines)	ORU, MB	5, 7, 10
	ORU heat exchanger	ORU	5, 7, 10
TCS-radiator system	heat pipes	2 fixed on RM	
	heat exchanger	8 mounted on PM2	5, 7, 9, 10
	flexible tubes		
PROP	biprop. tank	prop. ORU	6
	thruster	MB	8
EPS	relays	ORU	8, 12
	DC/DC converter		1
COMMS	antenna pointing mechanism	MB	2, 3, 4
SOLAR ARRAY	solar array drive	MB	2, 3, 4
STRUCTURE	bearings (joints, guides) bearing elements	RM, ORU	4, 14
GNC	reaction wheels	ORU	1, 2, 3, 4
	gyroscopes	ORU	1, 2, 3, 4

Table 5 : Original Causes of Induced Disturbances

NO.	KIND OF EXCITATION	CAUSE	CHARACTERISTICS
1	magnetic	excentric variable field in rotor circumferential direct.	spectrum of discrete frequencies
2	mechanical	dynamic/static imbalances of rotors	discrete frequencies
3	mechanical	bearing friction	broadband noise
4	mechanical	stiction-friction	impact
5	fluid stream	vortex shedding, cavitation	broadband noise
6	fluid motion	fluid sloshing	discrete frequencies
7	mechanical borne sound	structure borne sound transmission	broadband noise
8	mechanical	switch on/off events	impact noise
9	aerodynamics	vortex shedding, turbulent flow	broadband noise
10	mechanical	resonance vibrations excited by fluid stream	nearly pure tone
11	fluid stream	pressure fluctuations within pump medium	single tones
12	mechanical	inertia forces/moments of accelerated/ delayed masses	impact
13	aerodynamics	periodically alternating forces	single tones
14	thermal	struct. stress compensation	impact

System Data :

total mass	18000 kg
lenght	11 m
diameter	4.1 m
total el. power	10 kW
payload el. power	5 kW
data rate	20 MBPS
operational orbit	430–490 km

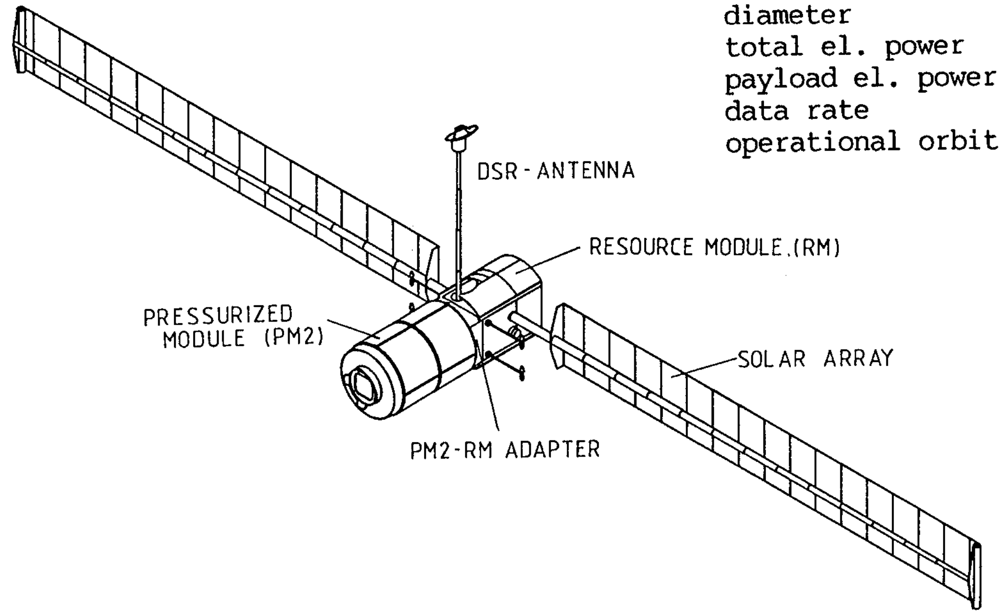

Figure 1 : MTFF Orbital Laboratory

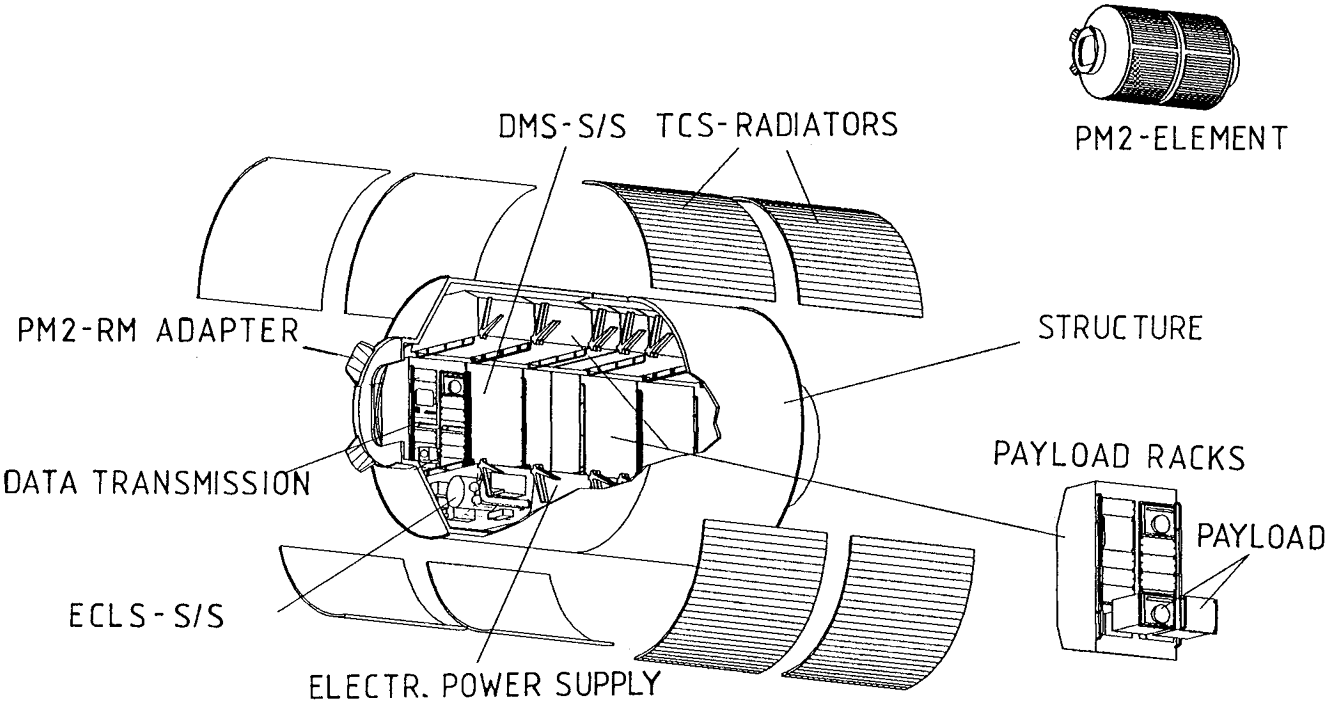

Figure 2 : Pressurized Module (PM2-Element) Exploded View

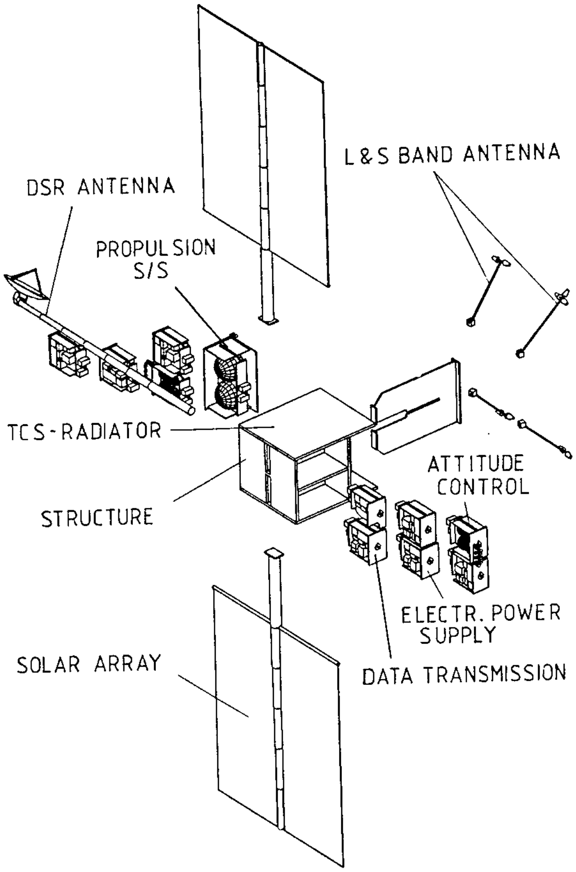

Figure 3 : Resource Module (RM-Element) Exploded View

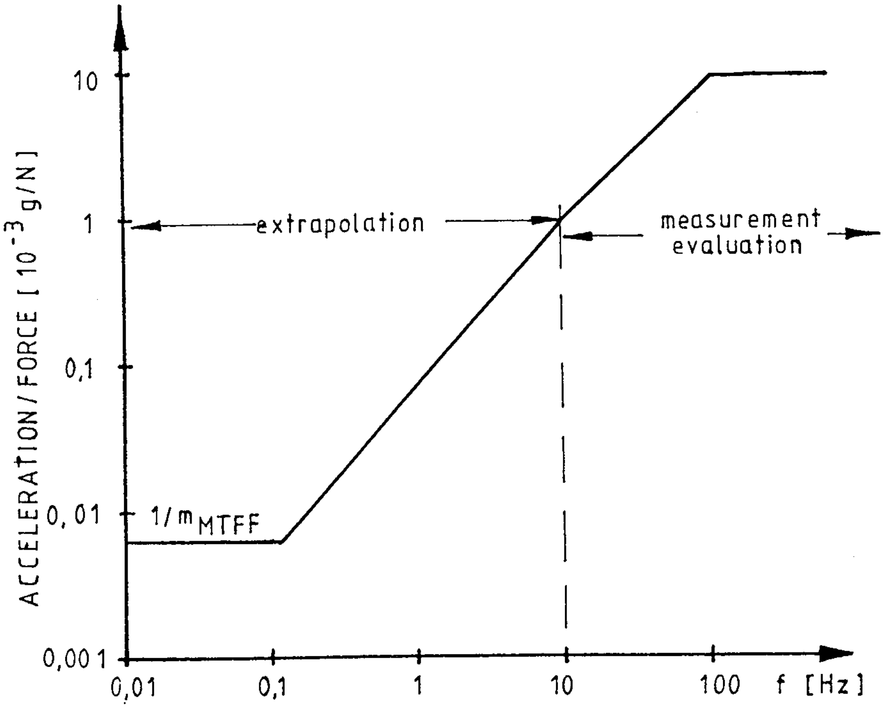

Figure 4 : MTFF Acceleration to Force Transfer Function
(Independent of Excitation Location and Direction)

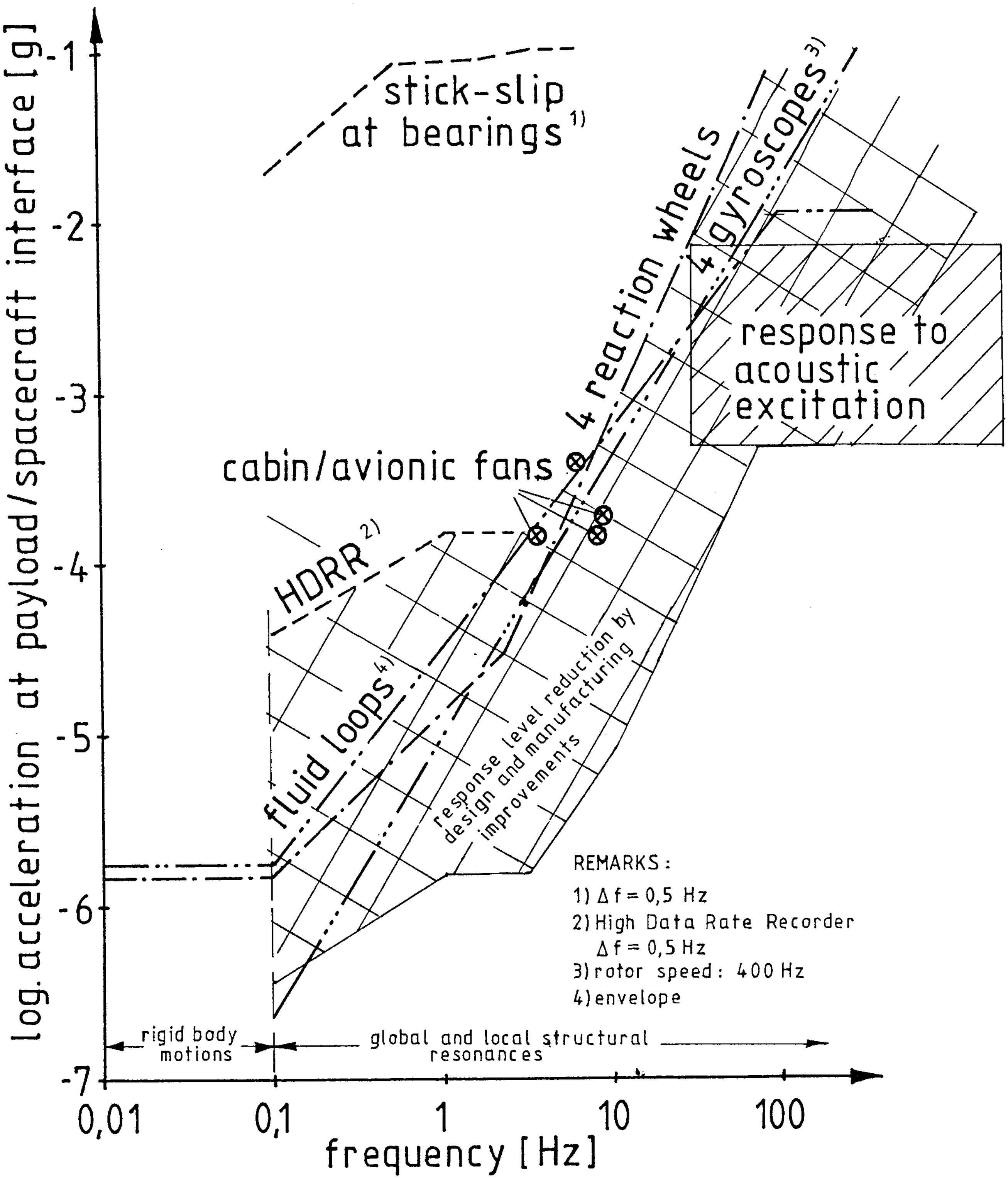

Figure 5 : Predicted Acceleration Response Spectra at Spacecraft/Microgravity Payload Interfaces

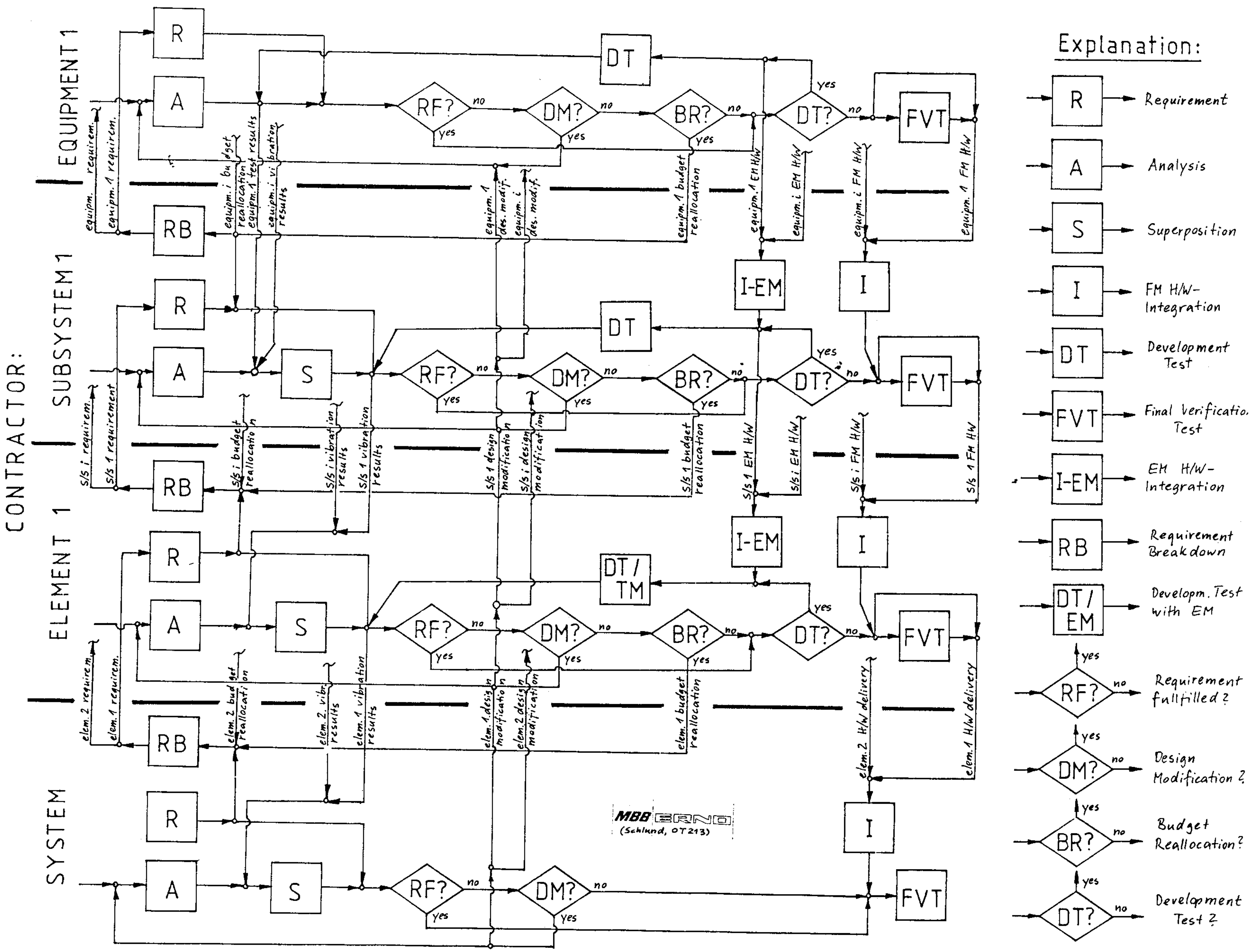

Figure 6 : Microgravity Control Flow Diagram

SYMBOLS AND ABBREVIATIONS

COMMS	Communication S/S
DMS	Data Management Subsystem
ECLS	Environmental Control and Life Support S/S
EM	Engineering Model
EPS	Electrical Power Distribution S/S
GNC	Guidance, Navigation and Control
HDRR	High Data Rate Recorder
I/F	Interface
MTFF	Man Tended Free Flyer
ORU	Orbit Replacable Unit
P/L	Payload
PM2	Pressurized Module, 2 Segments
RM	Resource Module
S/C	Spacecraft
S/S	Subsystem
STM	Structural Model
TBD	To Be Determined
TCS	Thermal Control S/S

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Session VII

LAUNCHER FACILITIES